Computer modelling of mixed age, polyspecific broadleaf woodland in the United Kingdom.

by

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ABSTRACT

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Commensurate with the increase in the planting rate of broadleaf species is the need to investigate forest management that uses mixtures of species and ages. Reliable data for woodland of this type is exceedingly rare and the need to advise managers is immediate. Management and investment decisions can be examined with models of forest growth and economics.

PART 1 Forest growth models.

Many models have been reviewed and the most appropriate selected for further development. This thesis concentrates on the improvement of distance independent individual tree models. This is a modelling approach that is compatible with current knowledge and ideas in ecology.

Several general improvements have been made. New growth equations have been produced and then calibrated to diameter increment data. Estimates for height prediction have been derived from analysis of a large survey of trees. Competition has been represented by a new multiplier, with a consequent improvement in the predicted diameter frequency distributions. The prediction of biomass for a given quality of site was modified such that control is mediated by measures of density dependence and biomass increment, via mortality.

Finally, the results from improved versions of the model were tested against the known change in diameter frequency distribution for Meathop Wood in Cumbria. The result showed a promising similarity, and the minor disparities appear to be linked to the modelling of regeneration.

PART 2 A forest economics model.

A new model to assess the relative profitability of a wide variety of management options has been devised. The model is easy to operate and allows comparison for many differing financial circumstances. It has been used for investigating the importance of major financial variables in the selection of forestry investments. Research into changing fiscal incentives, 'natural' management, and ideal planting densities for oak have also been completed by use of the model.

Publications resulting totally, or in part, from research presented in this thesis.

Adlard, P.G., Spilsbury, M.J. and Whitmore, T.C. (1988). Current thinking on modelling the tropical moist forest. ***IUFRO group conference proceedings, Malaysia 1988.***

Crockford, K.J., Spilsbury M.J. and Savill, P.S. (1987). The relative economics of woodland management systems. ***Oxford Forestry Institute Occasional Paper No 35.***

Crockford, K.J. and Spilsbury, M.J. (1987). The relative economics of different silvicultural systems. ***In OFI Occasional paper No 34 p.11-22.***

Spilsbury, M.J. (1987) and updated (1988) Woodman III - A User's Guide. ***Report for the Energy Division, UK Atomic Energy Authority. ETSU B1156.***

Savill, P.S., Crockford, K.J. and Spilsbury, M.J. (1988). Economic returns from farm woodlands. ***Farm Management 6 (9),*** 363-372.

Spilsbury, M.J. and Crockford K.J. (1989). Woodland Economics and the 1988 Budget. ***Quarterly Journal of Forestry. 83 (1),*** 25-32.

Winner of the James Cup (Royal Forestry Society), deemed best article for 1989 to be published in the Journal.

Spilsbury, M.J. (1990). The economic prospects for natural management of woodlands in the UK. ***Forestry 63 (4),*** 379-390.

Savill, P.S. and Spilsbury, M.J. (1991). Growing oaks at closer spacing. ***Forestry 64 (4),*** (in press).

Spilsbury, M.J. Height-diameter equations for commonly planted broadleaved species in the United Kingdom. (in preparation for Forest Ecology and Management).

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DEDICATION

This thesis is dedicated to Ronnie, my family, and friends.

ABBREVIATIONS AND GLOSSARY OF TERMS.

Units.

m	metres.
cm	centimetres.
mm	millimetres.
yr	years.
ha	hectares (10000 m^2).

Common Parameters.

D	diameter of a stem, usually at breast height.
dbh	diameter at breast height (130 cm).
D_m	Maximum recorded diameter for a species.
H_m	Maximum recorded height for a species.
G	Species specific growth constant.
Log	Common (base 10) logarithms.
Ln	Natural (base e) Logarithms.

Abbreviations.

BCR	Benefit-Cost Ratio.
BLS	Better Land Supplement.
BWGS	Broadleaved Woodland Grant Scheme.
CAI	Current Annual Increment (of a stand or a tree).
FGS	Forestry Grant Scheme.
FWS	Farm Woodland Scheme.
IBP	International Biological Programme.
IRR	Internal Rate of Return.
LEV	Land Expectation Value.
LFA	Less Favoured Area.
MAI	Mean Annual Increment (of a stand or tree).
NPV	Net Present Value.
NDR	Net Discounted Revenue.
SAS	Set-Aside Scheme.
WGS	Woodland Grant Scheme.

Glossary.

Biomass.
The aboveground (except where otherwise specified) dry weight of biological material, in this thesis usually referring to that produced by the tree component.

Climax.
Ecological term of limited meaning with regard to the development of a woodland over time towards a 'stable end point'. A relatively undisturbed woodland.

Polyspecific broadleaved woodland.
A woodland with many hardwood tree species.

Program.
A series of instructions in a computer language.

Systems analysis.
A defined framework for investigative research (see Foreword).

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FOREWORD

(i) Scope of study

This thesis covers aspects of computer modelling within specific contexts of forest ecology and forest economics. Various approaches to computer modelling have been examined and assessed with respect to the defined objectives of their application. Studies relevant to the further development of existing forest growth models, and the formulation of a novel forest economics model have been completed.

Research into modelling forest ecosystems has been restricted to mixed age, mixed species deciduous woodlands within the U.K. The main objective of this research was to obtain data and to adapt appropriate existing computer models, describing functional ecological relationships for mixed age, broadleaved polyspecific woodlands in the U.K. It is envisaged that this approach will lead to the production a model of sufficient accuracy and reliability to enable its use for investigating the management of a variety of forest systems in the U.K.

For investigations into woodland economics many forest management systems have been considered. An 'economics' model to facilitate the study of relative values and financial attractiveness for U.K. forestry investment under different circumstances of grants and taxation has been produced. Figure 1.1 shows a flow diagram of the research activities undertaken.

(ii) Models and Systems Analysis: a definition.

Any form of computer simulation (modelling) should be approached within a formalised framework. A working definition of the word 'model' in all its uses is required, as is a formal explanation of the framework applied in research of this type.

The Oxford English Dictionary defines a 'model' as; (i) "A summary, epitome or abstract....a description of structure" (ii) "a representation of some existing structure...that is a likeness or image of another....showing the proportions and arrangements of its component parts". The verb to 'model' is defined; (i) "To present as a model or outline....to produce an expression of a system....to make a tool".

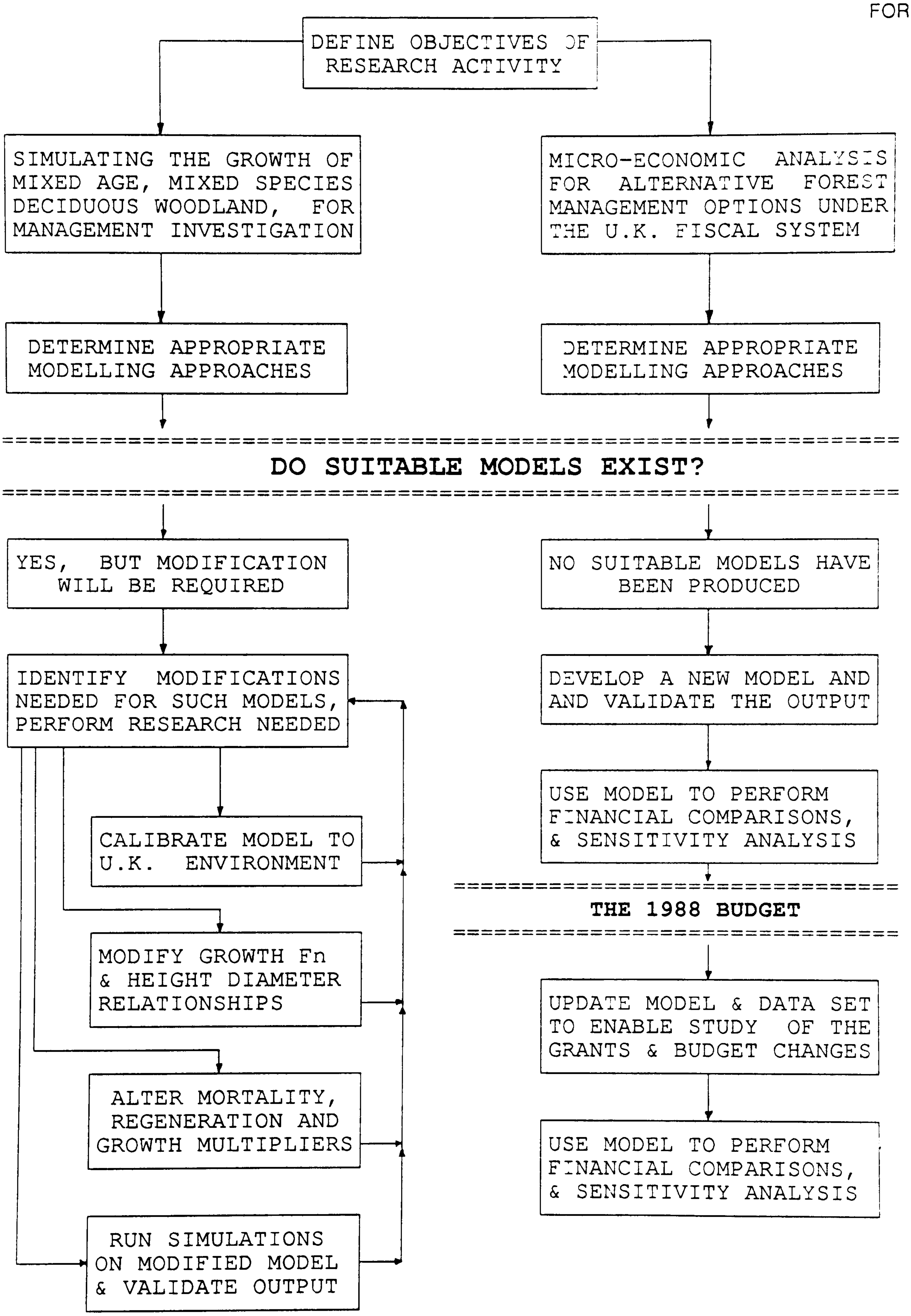


Figure 1.1. Flow diagram of research activities undertaken in this thesis.

Modelling, as applied to scientific research, involves representing the theoretical behaviour of real phenomena as mathematical expressions. They are particularly useful in cases where real time is inconvenient for practical experimentation or measurement, and in cases where forecasting is desirable. Assmann (1970) states; "mathematical formularization offers great advantages because it enables compressed statements to be made, and permits control over the certainty of statements by means of statistical methods." A model is collection of mathematical equations and data that are manipulated, usually by means of a computer. Indeed, Vanclay (1983) notes that the term model has only entered into common usage in forestry literature since the application of computers to the problems of growth and yield prediction.

The accepted approach to the study of complex systems using computer models is known as 'systems analysis'. This is the orderly and logical organisation of data and information into models, followed by the testing and exploration of such models necessary for their improvement. The purpose of the model being to represent important aspects of the biological system, and to highlight other important aspects requiring further study. Output from a model hopefully yields some useful information not readily derived from consideration of factors individually, using the computer to perform a large number of calculations in a minimum of time (Galea 1988). There are several important steps in the systems analysis approach (adapted from Jeffers 1978, 1982):

> **(i) Recognition of the problem;** or an interrelated network of problems. e.g. investigating species dynamics in a forest over time, or studying the economics of forestry investments.
>
> **(ii) Definition and bounding the extent of the problem.** Simplification of the problem into a form that can be solved, avoiding the dangers of over-simplification.
>
> **(iii) Identification of a hierarchy of goals and objectives.** Deciding the most important factors in the proposed investigation. The core of the problem being tackled first, only being concerned with desirable peripheral detail at a later stage.
>
> **(iv) Generation of solutions.** Families of possible solutions are considered, there may be more than one method of solution. One must select the most appropriate method to the problem in hand, remembering that the assumptions forming the basis of solutions must fit the system being studied.
>
> **(v) Modelling.** This is undertaken in the knowledge that many of the interrelationships will be uncertain. e.g. feedback systems, the intensity of their effect and the thresholds for their initiation. It should be remembered that the model is not an end to itself, but it is a formalised approximation, through existing knowledge, to the reality of the system under study. The goal is to produce the most accurate representation possible.

(vi) Evaluation of the model output (verification and validation). Once the model is usable, assess the sensitivity of the variables producing the results. The procedures for validation and verification may alter the assumptions used to date, causing a reiteration through preceding stages.

(vii) Implementation of the results. The application of a model to different situations can be attempted, however all predictions should be validated. Successful attempts at disproving the validity of the model cause further reiteration. Failure to disprove adds further credence to the model.

The systems analysis framework of study has been adopted throughout the course of this research. In essence it should be regarded as an aid to research designed to encourage frequent assessment of research activity with reference to the objectives of study. Inevitably, the success of a research project is seldom the result of a linear progression from one stage to the next, many 'blind alleys' are encountered. The systems analysis framework often assists in early identification of fruitless paths of study.

Chapter 1 applies this research methodology in the selection of a suitable model for the modelling of mixed age polyspecific broadleaved woodland in the U.K.

PART 1.

CHAPTER 1. Forest ecology and modelling.

> *'Employ your time improving yourself by other mens writings; so you shall come easily by what others have laboured hard for.'*
>
> *Socrates.*

1.1 Introduction

This chapter serves the purpose of a literature review, whilst identifying suitable approaches to modelling mixed-age mixed species, broadleaf woodlands.

In general terms ecology is concerned with the study of biological systems (often defined as communities, or more broadly as ecosystems) and the processes that influence them. Tansley (1935) defined an ecosystem (a fundamental concept) as "A system resulting from the integration of all living and non-living factors of the environment". The ecology of a system can be considered over many spatial and temporal scales.

Modelling of uneven-aged mixed species forest has been neglected, when compared to the vast number of studies carried out on even-aged plantations. Vanclay (*op. cit*) reports; "There is an extremely limited amount of information available on modelling techniques for uneven-aged polyspecific forest stands", whilst Miles (1979) comments "There is a need to be able to model vegetation change as a tool in the use, management and sustaining of biological resources."

Application of the systems analysis approach as a framework for the study of managed (predominantly deciduous) woodland in the U.K., demands an understanding of the important factors and interrelationships within such systems. This understanding is necessary in order to find the best approach to the investigation of the development of woodland in relation to the stated objectives of simulating management strategies in such woodlands. Good managerial practice must be based on sound knowledge of the governing ecological processes, and models designed to simulate woodland development or successional change must adequately describe the fundamental ecological processes that are of relevance for this purpose. However, the potential usefulness of any ecological model with respect to forest management will depend upon its theoretical basis and the modelling assumptions. Contemporary ideas regarding the theoretical basis of forest ecology must therefore be examined.

1.2 Historical background to forest ecology

Historically, discussion of the important factors influencing the development of forests has been an area of particular interest. Ecology is a relatively young science and much of the early work was largely of a descriptive or purely theoretical nature, centred on the classification or categorisation of ecosystems and the natural histories of the species residing within them. Much discussion concerning the ecology of vegetation has been centred upon the phenomenon of species succession (the change in the vegetational species composition of an area with respect to time). Spurr (1952) cites qualitative studies of European forest succession by Hundeshagen as early as 1830 and by Gand in 1840 but credits the first use of the phrase "forest succession" to Thoreau in 1860. The study of successional change has promoted a scientific argument that has developed during the twentieth century classically involving two general schools of thought. The holistic view put forward by Clements (1916, 1936) and the individualistic view proposed by Gleason (1917, 1927, 1939).

Understanding the ecological processes that drive patterns of forest development and species change, whether successional or not, is fundamental to the construction of a model for mixed-age, mixed-species forest growth. A model should, therefore, reflect the state of current knowledge, with observed ecological processes fitting the theoretical paradigm. The correct theoretical approach for encompassing the dynamic character of forested systems should be clarified.

1.2.1 The holistic conception of succession.

The holistic view emphasises the generality of successional changes in various ecosystems irrespective of the individual characteristics of the organisms comprising the ecosystem. Clements (*op. cit.*) saw successional change as a deterministic, irreversible, unidirectional progression through a series of stages (seres) to an end point known as the 'climax community' or 'monoclimax' (sometimes interrupted by natural disturbance to restart the process). Clements also held that successional change was driven by site modification (plant species altering the environment allowing other species to dominate). This view has been much criticised and Miles *et al.* (1988) write "His [Clements] speculative theory was fatally flawed from the outset, and has been criticised often and in detail, yet his influence on the development of plant ecology was profound". A modification of this viewpoint, developed from Nichols (1923), is termed 'polyclimax succession' with species change thought to progress towards a 'climax' but the precise nature of this 'climax' varying with specific biotic and environmental conditions.

1.2.2 The individualistic conception of succession.

The individualist view, developed from the work of Gleason (1937), stresses the importance of the individual characteristics of organisms within communities and how these relate to observed patterns which may (or may not) be successional. For example a successional sequence would be described in terms of the differing 'strategies' of individuals, as a result of an evolutionary selection pressure. Trorey (1932) seems to have considerable insight, commenting at the end of a paper on height prediction from equations based on diameter (for practical forestry purposes); "These mathematical relations present climax and tolerance in an interesting light, and when worked out for other species [than fir and spruce] may be an aid in predicting changes in future growth of mixed immature forest with respect to percentage of species". This insight forms the basis of the study of successional change, and highlights an approach adopted in many contemporary forest development models.

1.3 Successional climax or gap-phase dynamics?

The heterogeneity of the vegetational composition of 'natural' forests is a frequently cited observation (Oldeman 1978, Spurr and Barnes 1973, 1980, Bormann and Likens 1979), and the study of this heterogeneity over time can be described as gap-phase dynamics. Watt (1947) used the term 'gap' to refer to a site where a canopy individual has died and active regeneration of new individuals occurs. This terminology has subsequently entered into common usage in ecology and is no longer restricted to forest ecology, (Pickett and White 1985).

The individualistic theory is most likely to provide the approach best suited to computer modelling of forest ecology. One of the main problems with the application of the holistic approach to the development of forest ecosystems is the notion of 'climax community', a stable end point in a successional sequence, which has properties of self-maintenance. The 'climax' concept does not lend itself easily to the study of the dynamics of a forest system, even if the original assumptions of long-term stability are removed. This is demonstrable by simple theoretical consideration of commonly observed phenomena in forest dynamics.

Consider a large scale disturbance to a forest by a fire or a hurricane. This can effectively clear a large area of land which may then be recolonised, perhaps by a fast growing (pioneer) tree species (creating a near uniform age structure), slower growing longer-lived shade tolerant trees may, in time, grow up through the existing canopy and overshadow their fast growing intolerant competitors (successional change or forest development).

There is no difficulty applying either the holistic or individualistic theories up to this point. But if we consider the death of a dominant canopy tree from this stand, a 'gap' is produced. Gaps in the forest canopy may be colonised by a fast growing short-lived, shade intolerant species (assuming a seed source), thereby leading to a 'mosaic' type of forest with different stages of development or succession in the gaps. The application of the holistic view of forest dynamics, especially with regard to successional change, becomes problematical because it is impossible to define the spatial and temporal scales over which the processes leading to the 'climax' are acting. The idea that the 'climax' vegetation has a self perpetuating stability would require a definition of the spatial and temporal scales over which stability of the system would be expected. If the holistic approach is used as the fundamental concept, the heterogeneity expected within the forested system (via gap-phase dynamics) is not readily incorporated.

The present consensus is that species of all types are always adapting to change in the environment. Slowly changing Quaternary climates are an example of a driving force for adaptive change (evolution) and the idea that a particular environment has a predetermined stable conformation of species is not tenable, especially if the stochastic nature of frequency and scale of disturbance (endogenous / exogenous mortality) and species regeneration are also considered. "Succession does not necessarily require the progressive development to a 'climax' or mature state" (Shugart 1984).

These ideas together with more detailed understanding of the influence of disturbance upon forested systems have led to the study of the dynamics of these systems. "Convergent undisturbed succession is not normally found in nature" (Horn 1979). However it has been recorded at some sites, one early example of directional succession is provided by the colonisation of glacial spoil in North America (Cooper 1939, Lawrence 1958); other forested environments may have a 'sub-climax' stability in that the species are adapted to frequent disturbance by forest fires (Gray *et al.* 1987), some species require the high temperatures of a forest fire to allow germination of seeds held in resinous cones (e.g. *Pinus radiata, Pinus banksiana*) and are often found as natural monocultures. This is an illustration of the point that succession is not a universal phenomenon of forested systems but such systems are invariably dynamic. *Long-term stability in vegetation is the exception rather than the rule.*

"The individualistic school of forest succession is probably the dominant view of succession at present" (Shugart *op. cit*). It could be argued that it is *the only* tenable viewpoint since natural selection acts directly on individuals (or more correctly genes) within populations and certainly not on assemblages of individuals (Dawkins 1976), and this theoretical treatment is the only one to concur with current ideas in evolutionary biology. It is also an approach easily applied to the framework of study as defined by systems analysis. The individualist concept of forest dynamics is therefore recommended and will be applied to the aims of this research; investigating the fundamental factors in forest development and utilization of the knowledge gained to determine the consequences for a variety of forest management practices.

1.4 Systems analysis and forest ecology.

The properties of ecosystems or vegetation are of great interest to managers of such environments. Consideration of the basic ecology of dynamic forest systems is important in determining the approach taken towards modelling such systems. We can conclude that for theoretical consideration of gap-phase dynamics the individualist concept is the most useful.

(i) In the first step of the systems analysis framework the *problem is identified* as understanding the relative importance of biotic and abiotic factors affecting the growth of individuals of differing species and sizes/ages, and the relationship to the growth of other individuals.

(ii) Step two of the framework requires the *definition of the spatial and temporal scales* suitable for modelling, whilst encouraging the simplification, but not over-simplification, of other dynamic properties of the system. The most obvious simplification of reality, is to represent its constituent parts by means of numbers and mathematical expressions, these are related to one another in later stages (*iv* and *v*) of the systems analysis framework. In a forest ecosystem the main concern is to keep track of the processes of regeneration, growth and death of the woody primary producers. A justifiable simplification, for example, would be to ignore consideration of forest floor shrubs (if the primary interest is the perennial woody component). Another example could be determining net decomposition rates without consideration of the population levels of decomposers. If the objective is to capture the essentials of the dynamic processes within the system then choosing a sensible time scale for the measurement and prediction of change is important. Clearly one second is so short that the only measurable changes would be on a molecular scale, conversely if an interval of fifty years is chosen then so much change will have taken place that regeneration growth and death of many individuals will be missed entirely. In many models of temperate forests an interval of one year is chosen, this has the added convenience that seasonal patterns will be averaged, and repeated over this period. Tropical forests, on the other hand, may benefit from consideration of shorter time intervals for a forest dynamics model, due to faster growth and nutrient cycling rates. Aseasonality may also simplify the treatment of climatological factors in tropical regions.

Choosing the scale of the modelled area of the forest is of great importance. Too large a modelled area may demand prodigious computational power with no consequent improvement in the accuracy of predictions, however the chosen area must be of sufficient size to enable the effects of gap-phase dynamics to be perceived. Simplification can be achieved in a variety of ways, for example by the definition of species specific parameters. If the salient species characteristics are generalised, this will have the effect of eliminating intraspecific variation between individuals (genotype is assumed to be uniform), without prejudicing the possible significance of intraspecific competition between individuals (mediated through different phenotypes e.g. size of the individual).

(iii) The third step in the systems analysis framework, *defining goals and objectives*, must be to predict accurately the development of a section of forest over time whilst supplying a minimum of information. The predictions should be useful both in terms of understanding the ecology of the system and producing useful quantitative information, whilst also highlighting important factors requiring further study. The ideal is a model that can be used for predicting the effects of alternative management strategies of deciduous and mixed woodland of all types. A model that can cope with mixed age and mixed species should also be capable of dealing with even-aged or single species woodland management systems, but is likely to lack the computational efficiency of a model designed specifically for more uniform stands. Indeed, the modelling of even aged stands with such a model may provide a good test of the assumptions when results are compared to the growth data available, or to the output of forest growth models designed specifically for this purpose.

(iv) The *identification of families of possible solutions*. There have been many forest growth models but few approaches are suitable for the objectives of this study; namely a model that utilizes ecological relationships of individual trees with their environment and each other in order to predict the development of mixed woodland of even or uneven ages.

(v) Construction of computer models can be achieved by the use of a wide variety of computers, computer languages, and the development of many differing algorithms.

(vi) Shortcomings illuminated by *testing the model* or its components, (stage vi) may demand the need for complete reiteration of the framework, re-evaluating the problem at every stage. More simply, testing may indicate the need for modified programming or parameter values.

(vii) Finally, the completed model is implemented with the *results compared to the initial objectives*, (stage vii). Any shortcomings again prompt a reiteration through the stages of the framework. Systems analysis is not, therefore, a rigidly applied 'formula', but a flexible guideline to encourage the construction of a useful model that matches the objectives.

1.5 Classification of types of forest models.

Examination of different types of model is necessary in order to select the most appropriate approach for modelling mixed deciduous woodlands in the U.K. Suitable existing models are identified in this section and are later modified to suit the objectives of this study.

The 'fundamental modelling unit' (Munro 1974) has been employed as the basis for the classification of forest growth models. The models have been further grouped with respect to their objectives and the methods employed in their algorithms.

Contingent with all of the theoretical considerations is the realisation of the limitations of any model. Dale *et al.* (1986) comment "No model will ever predict all of the forest attributes precisely due to the complexity and variability of ecological factors affecting tree growth. The best models will explain the variation from the data and be appropriate for the questions at hand whether they relate to forest management or ecological succession".

Table 1.1. A classification of selected published growth models and references, (from Adlard, Spilsbury and Whitmore 1988).

Model type:- Row/Column		**Whole stand** A	**Stand class** B	**Individual tree** C
Approaches	1	Descriptive	Stand tables	Distance dependent
	2	Mensurational	Distributions	Distance independent
	3	Physiological	Representative tree	Gap dynamics
	4	Ecological		Physiological
Objectives	5	Description	Description	Description
	6	Growth forecast	Growth prediction	Ecological research
	7	Global models:-	Yield prediction	Predict succession
	8	(biological)	Regional/local plan	Monitor growth
	9	(economic)	(silviculture)	Predict environmental
	10	Monitor environment	(management)	impacts
	11	Regional planning	(economics)	(disease)
	12		Predict succession	(air pollution)
Variables	13	Basal area	Size class	Diameter
	14	Dominant height	(diameter)	Height
	15	Stand density	(height)	Crown percentage
	16	Canopy structure	Species	Crown area
	17	Leaf area	Age (cohort)	Growing space
	18			Near neighbours
Methods	19	Regression	Stand table estimate	Growth equation
	20	Growth functions	Transition matrices	(max growth of spp.)
	21		Empirical equations	Growth modifiers
	22		Simultaneous equations	light attenuation)
	23		Differential equations	(temperature)
	24		Distribution functions	(nutrients available)

Table 1.2. References associated with Table 1.1 by row and column.

Row/Column	Author	Date
A2/B23	Leary	1979
A1	Clutter	1963
A4	Detwiler and Hall	1980
B2	Campbell *et al.*	1979
B3	USDA	1979
B6	Hahn and Rolfe	1979
B6/7	Daniels and Burkhart	1988
B7	Hanson	1913
C1	Mitchell	1975
C1/C19/C20	Ek and Monserud	1974
C2	Alder	1977
C2/C8	Rennolls and Blackwell	1986
C3	Botkin *et al.*	1972
C3/C11	Shugart and West	1977
C6	Pastor and Post	1985
C7	Dale and Hemstrom	1984
C9	Dale and Gardner	1987
B23	Shugart *et al.*	1973
B15	Monserud and Ek	1977
B14	Campbell	1981
B19	Whalenburg	1941
B20	Bruner and Moser	1973
B20	Usher	1966
B20	Michie and McCandless	1986
B21	Grimes and Pegg	1979
B21	Ek	1974
B21	Revilla	1981
B22	Leary	1970
B22	Moser	1974

For further references see Dudek and Ek (1980) and Ek *et al.* (1988a and b).

1.5.1 Whole stand models.

These types of models are usually developed from data describing stand growth. For example, they may be developed to estimate increases in volume or basal area for different species under different conditions of management and stocking. Yield tables have been used in European forest management since 1787 (Vuokila 1965, in Vanclay 1983) and can be regarded as simple 'models' in that they predict future yields. Standard Forestry Commission yield tables (Hamilton and Christie 1971) are simple growth curves for different species growing at different rates (to account for site and, presumably, genotype variability), a standard spacing and management regime is assumed. Updated yield tables (Edwards and Christie 1981) allow for variable stocking and thinning levels. Both the above provide information on yield in terms of volume production and give information on mean stand parameters such as diameter, height, numbers of stems, mean annual increment and current annual increment (mean periodic increment) for different stand ages.

The foremost limitation of a yield table is the restriction to even-aged stands of known age and, additionally, predetermined management assumptions.

A variety of approaches to stand models have been developed including growth and yield equations of both an empirical and a theoretical character. Growth equations have greater flexibility as they can be modified at different points in the development of a forest crop to account for changes in management. Clutter (1963) produced an empirical yield equation and its first derivative, a growth equation;

$$Ln\,V = b_0 + b_1S + b_2(Ln B) + b_3A^{-1}$$

The first derivative of this with respect to age being;

$$\frac{dV}{dA} = b_2VB^{-1}\left(\frac{dB}{dA}\right) - b_3VA^{-2}$$

Where; A = Age, S= Site Index, B = Basal area *Ln*V = Log Volume.

For the purposes of modelling mixed species and ages in the same stand it is reasonable to eliminate the stand model approach (analogous to applying a holistic theory of forest dynamics) from the range of potential solutions considered at stage (iv) in the systems analysis approach. This is due to the inflexibility of this approach in accounting for the different components of size, age and species in a stand, and other factors affecting their growth and management.

1.5.2 Stand class models.

Stand class models are a further sub-division of the stand model classification. This type of model uses a class of trees as the fundamental modelling unit. The division is usually made in some size parameter for a tree growth model, most commonly diameter. However species, or forest type can also serve to define the different classes within a stand. Models have been developed to predict forest growth and yield, economics and successional sequences. For cited examples refer to Tables 1.1 and 1.2.

The stand class model approach offers greater flexibility since any aspect of the stand may be partitioned according to the objectives of study. It is appropriate to consider a few highly selective examples to illustrate the advantages and shortcomings (steps *v* and *vi*) of the stand class approach to modelling woodland development with respect to the objectives of this study.

Stand modelling and stand class modelling are often associated with volume prediction in commercial forests, and there are many examples of this. But it has also been used as an approach to the modelling of succession.

There are a number of possible methods in constructing stand class models such as:

(i) Differential difference equations.
(ii) Markov/Leslie/Usher Transition matrices.
(iii) Distribution functions.
(iv) Empirical equations.
(v) Stand table projection.

Some of these approaches have been used for growth modelling in a uniform stand and for modelling species change over time in a 'natural' unmanaged (ie. mixed-age, mixed species) forests. Examples from the first two categories are discussed here to illustrate the limitations of stand and stand class approaches. For a detailed review of a large number of growth and yield models, including (i)-(v) above, refer to Fries (1974) and Vanclay (1983).

1.5.2.1 Differential difference equations.

Shugart's model (1973) represents a regional succession by a number of stand trajectories through a species/density 'hyperspace' (Figure 1.2.). The relative frequencies of the species determine the boundaries of each 'cover state' (stand class). A cover state is a defined

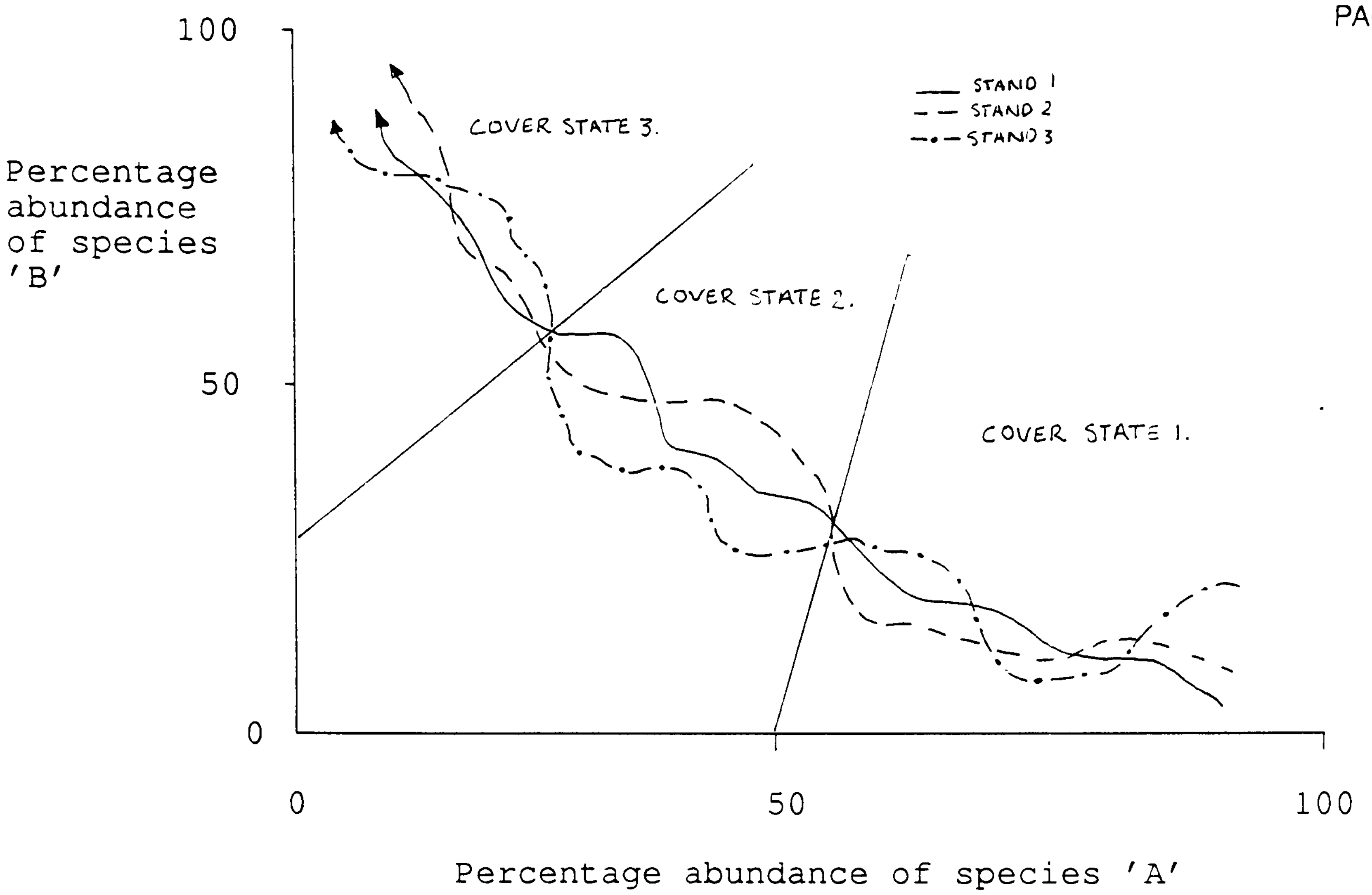


Figure 1.2 Changes in stand composition by species over time. Lines represent the development of different hypothetical stands (Shugart 1973)

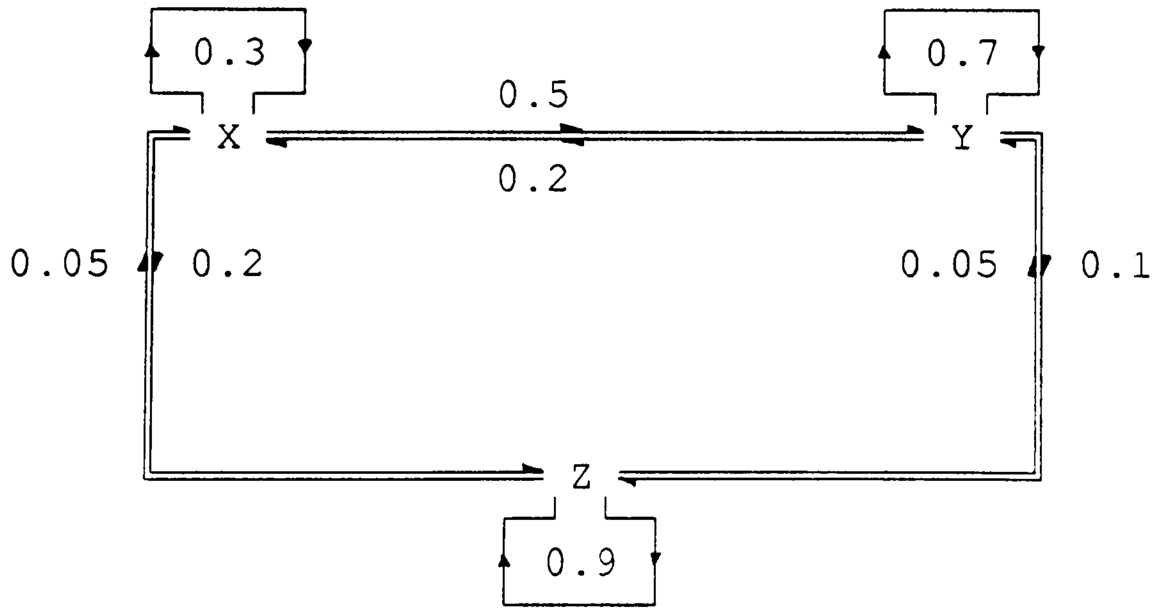


Figure 1.3. A diagram to represent transition probabilities between stand types X, Y and Z (Tucker and Fitter 1981). (Section 1.5.2.2.)

assemblage of species representing different stages of forest development in a directional successional sequence.

SPECIES	Birch	⇒	Ash	⇒	Hemlock
COVER STATE	1		2		3
	x_1		x_2		x_3

To describe succession in this system a series of differential equations representing species change are set up.

$$\frac{dx_1}{dt} = F_1 - C_{12}x_2$$

$$\frac{dx_2}{dt} = C_{12}x_1 - C_{23}x_2$$

$$\frac{dx_3}{dt} = C_{23}x_2$$

The frequencies are determined by the differential equations expressing transfers of numbers of individuals between cover states. Where;

$$C_{ij} = \frac{1}{a_{ij}}$$

and; a_{ij} = The time taken for 63 per cent of cover state 'i' to change to cover state 'j'. F_1 is a constant expressing the colonisation by birch (in this example).

Transfer parameters are determined from field data and the model is then used to predict species change in the future. This is the simplest system in Shugart's model. He considered several different cover states in addition, all of which interact with one another by further series of differential equations.

Leary (1970) uses a similar set of differential equations to investigate the productivity of a hardwood forest system in the USA. The size attribute selected for defining the stand class was based on diameter. The system of equations was solved by simultaneous methods using boundary values between classes; Moser (1974) presents a more comprehensive model, again creating artificial stand classes by the categorisation of diameter values. Numbers of trees in the diameter classes are projected through time, based on recurrent inventory of permanent sample plots (1926-1931). Differential difference equations are constructed to model basal area increases, volume increases, and mortality of trees for all-aged northern hardwood stands. For example the volume equation for the largest diameters (stand class 6) would be;

$$Y_{6,3} = Y_{6,3}(t_0) + Y_{6,6} - Y_{6,9} + Y_{6,11}$$

Where; $Y_{6,3}$ = Volume of the stand class 6 trees at any time providing $t \geq 0$.

t_0 = An initial time.

$Y_{6,6}$ = Volume of the ingrowth trees into the stand class.

$Y_{6,9}$ = Volume of the mortality trees.

$Y_{6,11}$ = Cumulative volume growth of the $Y_{i,1}$ trees in the time interval $t_0 - t_n$.

($Y_{i,1}$ = No of trees in stand class i at given instant.)

Moser (1974)

Problems with this approach to forest modelling are; (i) It relies on classification of forest types into cover states or size classes, this is almost always an arbitrary division of a continuum. (ii) It assumes a uniform change across the entire forest. This may be useful for general predictions, but tells us nothing about the causal factors behind any trends of species replacement or tree growth. (iii) Models are deterministic and will always produce the same output. This is in contrast to the processes of mortality and regeneration acting on individual trees, known to be highly stochastic. (iv) It is limited to generating information relating to the defined variable only, and (v), there is only limited flexibility for application to forest management practices, nor (vi) does it relate any 'tree parameters' to environmental factors affecting forest dynamics. In fairness to the authors the above examples were never intended for anything other than predicting species replacement, or stand development over large areas. These limitations, however, restrict the wider application of stand class models and make them wholly unsuited to the modelling of gap-phase dynamics.

1.5.2.2 Matrix models.

Matrices containing probability estimates for changes between predetermined states can be constructed and used as the basis of a model to predict change over time. Such matrices are described as transition matrices. These are constructed by observing the frequency with which a system moves from state *i* to state *j* in a set time interval. A transition matrix is made up of row vectors, each row vector consists of all the probabilities of change to other states. All states of the system are usually defined and therefore the probabilities in each row of the matrix will sum to one. The assumptions that have to be made in order to use this technique for making future predictions concerning a system are; (i) The probabilities of future events must depend only on the initial state, (ii) these probabilities remain constant over time.

Markov matrices and Markov chains are the general terms often used to describe this application of matrix and probability theory. A Markov chain is the successive application of a transition matrix to information concerning the initial condition of a system, generating a 'chain' of states through which (it is envisaged) a system will pass. A particular use of matrices, known as Leslie matrices, has arisen in biology to cope with animal population studies. The transition matrix describes three fundamental processes governing the behaviour of populations; growth, fecundity, and mortality. This approach has been applied to forest modelling.

Tucker and Fitter (1981) present a simple model to predict a successional sequence in an area of woodland near York using a matrix approach. X,Y and Z are defined as species or cover states. A 'state vector' [x,y,z] is derived from field data. This vector holds the number of individuals of each species or cover state. Similarly from observed data of species change within an environment a matrix of transition probabilities is derived. The matrix of transition probabilities associated with Figure 1.3 (page 17) can be produced;

$$M = \begin{bmatrix} 0.3 & 0.5 & 0.2 \\ 0.2 & 0.7 & 0.1 \\ 0.05 & 0.05 & 0.9 \end{bmatrix}$$

The state vector m_t = [x y z] at time $_t$. At time $_{t+1}$ the state vector $m_{t+1} = m_{t+1}.M$. Thus at time $_{t+2}$ the state vector $m_{t+2} = m_{t+1}.M = m_t.M.M = m_t.M^2$. Hence the state vector at time$_k$ = $m_{t+k} = m_t.M^k$. Another matrix relationship can be described by the equation;

$$M.m = \gamma.m$$

Where; γ = a constant known as the Eigenvalue or latent root of the matrix M.

Usher (1966,1967) uses Markovian probabilities to simulate growth in a Scots pine mixed age selection forest (with no definite regeneration phase) using a modified Leslie matrix approach. The modification specifies that progression between different classes defined in the system can only occur between one class and the next, e.g. different sizes of individuals growing in a stand can only progress by transition through each defined size class. The time interval between projections, must be selected such that this assumption will represent the actual system i.e. growth between projections will not exceed the defined limit of the next size class. This assumption is termed "the Usher assumption" by Vanclay (1983) and has been used in many subsequent models. A tree in any one defined class can either remain in that size class during the period over which the matrix operates, or can progress into a larger size class. In Usher's model the size classes are defined by diameter and the period of growth projection for the matrix is six years.

A simple version of the model (Usher 1967) was intended for teaching purposes, but will serve for the purposes of demonstration. From field data it was determined that 30 per cent of small pole trees become large pole trees, 40 per cent of the large pole trees become small timber and 75 per cent of the small timber trees are exploited. A gap produced by death or removal of a large pole tree would be filled by 4 small pole trees and a gap from a small timber tree would be filled by 12 small pole trees.

$$\begin{bmatrix} 0.7 & 4(\gamma-1) & 12(\gamma-0.75) & p \\ 0.3 & 0.6 & 0 & q \\ 0 & 0.4 & 0.25 & r \end{bmatrix} = \begin{bmatrix} \gamma p \\ \gamma q \\ \gamma r \end{bmatrix}$$

The matrix contains three rows and three columns and has three possible solutions for the latent column vector (p,q,r) and the latent root γ, derived from the equation involving γ described above. Only one of the three solutions produces a positive value for the number of trees present and the number of trees harvested at any given time. The 1966 model is more complex and was used to determine the best size (age) structure for sustained maximum production from a Scots pine selection forest. More recent examples of the matrix approach applied to forest development and management problems include; Bruner and Moser (1973), Buongiorno and Michie (1980), Harrison and Michie (1985), Michie and McCandless (1986).

The advantage of this type of model is that it requires very little data to obtain a prediction of the successional changes or growth of a stand. However, its greatest weakness is that it is based on the premise that the transition probabilities that drive the growth or successional change remain constant over time (from the initial state onwards) and, as a stand model, has to assume spatial uniformity and homogeneity of the environment. These are very major assumptions and constant transition probabilities make the model wholly deterministic (despite the fact that it uses probabilities). The model is limited to showing facets of the dynamic forest ecosystem in holistic manner. The probabilities used describe the 'net' effect of environmental factors on the aspects of the system that are modelled. The form of solution likely to yield more information concerning the primary ecological processes, and for modelling of mixed-age, mixed species forests will be based on individualist (individual tree) principles. This approach will be examined in more detail.

1.5.3 Individual tree models

These models can be classified according to the approach used to model the growth of an individual tree and its relationship to its immediate neighbours.

(i) Physiological models.
(ii) Distance dependent models.
(iii) Distance independent models (gap models).

Shugart (1984) presents a classification of growth models and makes a distinction between individual tree models and 'gap models', the distinction being that a gap model simulates tree regeneration, growth and mortality on a small plot. However, *the individual tree remains the fundamental modelling unit in a 'gap model'*.

1.5.3.1 Physiological models.

Physiological models can cover a wide range of approaches from detailed modelling of fundamental physiological processes (integrating them to simulate growth), to a more simplistic approach e.g. separating a tree into the components; crown, stem and roots.

Physiological individual tree models represent the ideal goal of being able to represent the response of an individual tree to all environmental factors, on any site. The problems with this approach are that many of the fundamental relationships between physiology and the external environment remain unknown, especially when the levels of the various environmental factors are considered in combination with the genetic variability of individuals. Even if all the relationships were known, the amount of data and the computing power required to run such a model would be prohibitive. Physiological models will be important for research and development in the future, especially as computer hardware becomes more advanced. However, the main limitation will remain the availability of data to construct and verify such models. Harrison and Ineson (1988) comment "this problem is particularly relevant to work in the U.K. for there are only two mixed deciduous woodland sites for which there are sufficient information on tree productivity, soil and nutrient cycling data, for modelling and some degree of validation".

1.5.3.2 Distance dependent models.

Distance dependent individual tree models utilize competitive interactions between individual trees to a significant extent. All models of this type simulate growth by assuming that the rate of growth is inversely proportional to the degree of competition for various resources. The limitations to growth are assumed to decrease as a function of increasing radial distance. Fries (1974) regards Newnham's model (1964) to be the first of this sort, and the basis for much of the subsequent work. The underlying assumptions are (i) that a maximum growth rate is represented by an open grown tree, (ii) decrease in growth rate from this maximum is proportional to the intensity of competition and (iii) mortality occurs when diameter increment falls below a critical threshold level.

Perhaps the most elaborate model of this type is FOREST (Ek and Monserud 1974). The input required is a set of tree co-ordinates, and associated individual tree characteristics (height, diameter, age, species, bole length). Trees are then 'grown' over set projection periods to a maximum potential growth rate which is then reduced by an index of competition. The competition index is based on relative size, crowding and shade tolerance. Processes of mortality and regeneration in the model can be manipulated to simulate forestry management practices. The model makes use of spatial data for calculation of competition indices and therefore the potential effect of any tree upon any other must be defined. This is achieved by delimiting 'zones of influence' for each tree and calculating the potential overlap of such a spatial configuration of tree canopies. The FOREST model also has methods to reduce bias favouring increased growth due to edge effects, these are not included in the original work by Newnham.

Problems with the distance dependent model are that specific spatial data from stands, ideally with many years of remeasurement, are required in the processes of development and validation/verification. Noble (*pers. comm.* 1987) stresses that distance dependent models do not greatly improve the accuracy of predictions compared to similar distance independent individual tree models. However, were such detailed continuous forest inventory available this contention could be more thoroughly tested.

1.5.3.3 Distance independent tree models (gap models).

The major difference between this approach and that described in section 1.5.3.2. is that the spatial distribution of individual trees is not simulated within these models.

Perhaps the most successful example of this approach to the modelling of the forest ecosystem was pioneered by Botkin *et al.* (1972) who developed the JABOWA model. It has been a highly successful approach and many derivatives of the original model have been applied to many different forest environments, for example by Shugart and West [FORET] (1977), Aber and Melillo [FORTNITE] (1978), Shugart and Noble [BRIND] (1981) to name but a few. Interactions within the system are developed from a consideration of the processes of the growth, death and regeneration of individual trees. The theoretical basis for this type of model is the individualistic school of ecological thought. This approach to modelling offers the greatest flexibility for development for a large number of applications and forest types including mixed-aged and mixed species.

This classification of model was adopted for further study on the basis that it conforms with theoretical considerations, whilst not demanding the specific spatial data from comprehensive recurrent inventory required by distance dependent models. Such inventory data does not exist for mixed age polyspecific broadleaved woodlands in the U.K. The use of distance independent models circumvents this limitation.

1.6 Components of the original gap model.

Having selected the most appropriate modelling approach, the general form of these models requires discussion in order to highlight components of the model that require modification through further research.

Botkin's model (1972) simulates the dynamics of forest gaps by following a plot of individuals through time. It will, for example, show a flush of regeneration on the forest floor after the death of an upper canopy dominant. The original model was based on experiments and data collected from the International Biological Programme (IBP) studies at the Hubbard-Brook ecosystem site in north-eastern USA (Reichle 1981). The form of the computer program is a 'current accounting' system that holds data describing each individual tree in memory. The 'accounts' are updated when the processes of growth, death and regeneration have been modelled in any one year for every tree. Thus the forest plot will show growth, death and regeneration in the computer, and all modelled facets of the system can be followed over time (which is greatly accelerated by the computer).

Since many models have been derived from the original formulated by Botkin *et al.* (*op. cit.*) this model will be considered in detail.

1.6.1 Overview of the JABOWA model.

Tree species within the JABOWA model are defined by a variety of parameters, for example; maximum age, maximum diameter, temperature limits to growth, ~~maximum age~~ and shade tolerance. A relationship between diameter and leaf weight is also defined as well as a photosynthetic rate in response to available light. All these are scaled by a growth constant 'G' designed to match the annual increment of the maximum observed growth rate for a particular species. This growth parameter is chosen so that the tree height reaches 2/3 of its maximum at half the maximum age of the species. "Species strategy is invoked by species specific survival probabilities of the shaded sapling in relation to light on the forest floor. Also, because of maximum age any individual will have a greater chance of survival to the next year if it is a long-lived species" (Botkin *et al., op. cit.*). The model is set up so that the probability of an individual surviving to the maximum age and diameter for the species is very low, i.e. mortality is an empirical probability function.

1.6.2 The growth equation.

This will be dealt with in great detail in chapters 2 and 3. In essence, the growth of trees on a JABOWA modelled plot is approached by calculating the increment of each individual stem. The growth of each stem is dependent upon its species and size.

$$\frac{d(D^2H)}{dt} = G.D^n \left(1 - \frac{D.H}{D_m.H_m} \right)$$

Where; D = dbh, H = height, G, D_m and H_m are species constants.

The silvicultural characteristics of each species are defined, and are set to represent maximum growth rates.

1.6.3 Multipliers to the growth equation.

Growth conditions for an individual are seldom optimum and, for this reason there are a series of multipliers associated with the growth equation. All of the growth multipliers are scaled between 0 and 1 and represent the decrease in growth from the optimum rate allowed. For example a growth multiplier of 0.5 would halve the existing growth rate. Growth multipliers are applied for parameters such as available light, temperature and the intensity of competition.

These multipliers are all included in the original growth equation (Botkin *et al.* 1972);

$$\frac{dD}{dt} = \frac{G.D\left(1 - \frac{D.H}{D_m H_m}\right)}{274 + 3b_2D - 4b_3D^2}.r(AL).T(DEGD).S(BAR)$$

Where; r(AL) represents the effect of shading of an individual, the shade tolerance of the species and the level of incident sunlight. T(DEGD) considers the climatological effect on the species by the relationship between the geographical distribution of the species and annual temperature variations. S(BAR) is an index of the maximum biomass sustainable by the site and is used to indicate the degree of competition experienced by an individual tree. Each of these multipliers will be considered in greater detail.

1.6.3.1 Light attenuation.

To simulate light attenuation through the canopy, all the trees on the simulated plot are ordered by height, and light is assumed to pass through each successive canopy. No spatial considerations other than the two dimensions are used. The canopy of each individual is represented by a single layer (area) of leaves over the plot. This is for easy calculation of light interception. Radiant light energy is assumed to attenuate through the canopy following Beer's law. Given the incident sunlight and the leaf area the light extinction can be calculated from:-

$$Q(h) = Q_o.\exp. -k \int_h^{\infty} LA(h').d(h')$$

where; $LA(h')$ = Distribution of leaf area as a function of height, Q_o = Incident radiation, $Q(h)$ = Radiation at height h, and k = Light extinction coefficient.

This is approximated by summation of the leaf areas of trees taller than the 'object' tree.

$$AL = PHI.e^{-k.SLA}$$

Where; AL = Available light for a given tree, SLA = Shading leaf area, from $\Sigma weight = C_iD^2$, PHI = Annual insolation and k = the Extinction coefficient. The reduction in growth associated with shading is denoted r(AL).

$$r_s(AL) = 1 - \exp.^{(-4.64(AL - 0.05))}$$

$$r_t(AL) = 2.24 \left(1 - \exp.^{(-1.136(AL - 0.08))} \right)$$

Where; $r_s(AL)$ = Representation of photosynthesis rates for shade tolerant species and $r_t(AL)$ = Representation of photosynthesis rates for shade intolerant species

The equations expressing photosynthesis curves fit observed data from the Hubbard-Brook study and are scaled to give values between 0 and 1. There are physiological and morphological reasons for 'shade tolerance'. Kozlowski (1960 in Shugart 1984) states "[Tolerance is the] capacity to endure shade. A tree which reaches maximum photosynthesis at relatively low light intensity is tolerant, while one whose rate of photosynthesis continues to increase with each added increment up to full sun is considered intolerant". Clearly a combination of the geometry and the physiological response to light determine the tolerance to shade of tree species. The above functions for light attenuation in a forest canopy are for forests in the east of the U.S.A. and verification/validation of similar canopy properties is required for adaptation of the model to conditions found in the U.K.

1.6.3.2 Temperature response (species limits).

The temperature multiplier assumes that each species will have an optimum temperature for maximising the rate of photosynthesis, and that rates will decline symmetrically on either side of the optimum. The temperature function is parabolic and is expressed in growing degree days set at a base temperature of 40° F (for JABOWA).

$$T(DEGD) = \frac{4(DEGD-DEGD_{min}).(DEGD_{max} - DEGD)}{(DEGD_{max} - DEGD_{min})^2}$$

DEGD is an annual measure of the days suitable for plant growth where the growth threshold is assumed to be 40° F. The number of degrees over this base temperature for the average temperature of a single day is summed for the year. However these data are usually not available and the values are approximated from the July and January averages. Thus $DEGD_{max}$ and $DEGD_{min}$ describe the geographical temperature boundaries within which the species can be found. These geographical boundaries correspond well with the thermal isopleths of degree-days.

From a theoretical standpoint the fundamental ecological niche for the species resulting from this multiplier, will be less than the realised ecological niche observed in natural conditions. This can deduced by consideration of $DEGD_{max}$ or $DEGD_{min}$. These are defined as the highest/lowest temperatures found in the range that the species occurs, and are derived from species distribution data in the field, thus we have data concerning the limit of the realised niche. However, upon substitution of the maximum or minimum values of DEGD into the function in the model we can see that the growth multiplier obtained is zero. i.e. no growth can occur and individuals of this species will 'die' as far as the model is concerned. Growth multipliers begin to increase as temperature moves towards the optimum for the species.

In effect then, the fundamental niche for a species is smaller in the model than the realised niche taken from data in the field. This marginal inaccuracy is largely irrelevant for management purposes as it is unlikely that a tree of marginal climatic suitability will be a significant component of the crop in a managed forest regime. However there are implications for modelling the growth of tree species occurring on the margins of their geographical distribution, but these are unlikely to be relevant for most broadleaved species in the U.K. and therefore so is this multiplier.

1.6.3.3 Competition for a limiting resource.

The final growth limiting multiplier used in the JABOWA growth equation is an expression of competition for moisture, space and nutrients with other individuals on the simulated plot. The function works by setting a maximum basal area (derived from maximum biomass data in the field) for the particular forest type under study. Thus by defining different maximum basal area values a measure of site class is included. However the premise implicit in this function is that forests free from exogenous disturbance, tend towards an equilibrium in terms of biomass. Fortunately such evidence exists. Pienaar and Turnbull (1973) observed that even-aged plantations, with spacings above a certain minimum level, converge towards an identical basal area per hectare. The absolute value of this maximum amount of basal area is dependent upon the quality of the site, the more fertile sites being capable of sustaining a greater maximum biomass. The competition multiplier used in the JABOWA model is shown below.

$$S(BAR) = 1 - \frac{BAR}{SOILQ}$$

BAR = Total basal area on the modelled plot, SOILQ = Maximum basal area possible for a plot.

The rationale behind this simple expression of complex competitive interactions on a site is that as the basal area of the plot increases so does competition for resources, increased competition being reflected in each individual through reduced growth rates. The two are related by a simple linear expression in the model. It is assumed that as a single unspecified resource becomes limiting it will affect all individuals equally, *no account of the likely advantages of relative size of individuals in competing for limited resources is considered.* Thus each individual is multiplied by the same growth multiplier for competitive interaction, and competition rises toward a maximum as basal area approaches a maximum. It should be remembered that the implication of this function is that the maximum biomass predicted by the model is not independently generated. No account of variations in nutrient availability is made, nutrients are assumed to reduce and not cycle. The size of plot is delimited by the maximum biomass the plot area can support. Clearly this part of the model is inaccurate due to over-simplification (see section iv of systems analysis framework).

1.6.4 Stochastic influences on forest development.

Modelling of forest dynamics must include the processes of both reproduction and mortality (as well as growth) of stems from year to year. These are processes that do not always follow a predictable pattern and, as such, lead to the stochastic nature of forest dynamics.

1.6.4.1 Mortality.

Mortality trees can be influenced by chance happenings, for example freak storms can cause widespread damage and tree death. Other exogenous disturbances include fire, landslides and earthquakes. Some of these are more likely than others in various parts of the world. There are, nonetheless, some consistent patterns in tree mortality of 'undisturbed' forest. Large numbers of seedlings may occur when there is a gap or open ground to colonise, but only very few will survive to maturity. This stage of forest development is subject to considerable variability because the numbers of seedlings regenerating are dependent upon many environmental and climatological factors. The pattern of mortality in even aged stands has, however, been a topic of much study. Notable work was carried out by Yoda *et al.* (1963) to produce the '-3/2 law of self thinning'. This describes a relationship between the maximum mean size of individuals (expressed in dry weight) and the stand stocking density. More recent work by Hamilton (1990) covers mortality functions in relation to forest growth models

In a mixed age, mixed species stand the problem is more complex and many approaches to the modelling of mortality use empirical survival probabilities that are linked to tree growth parameters. Due to the numbers of seedlings present at establishment, the probability of mortality for any one seedling is quite high (many never reach maturity). Once a tree becomes established, however, the probability of mortality is reduced.

In the JABOWA model only 2 per cent of saplings reach the species specific maximum age (AGEMAX). A constant mortality probability for the death of a tree in any one year is applied.

$$p = 1 - (1 - \varepsilon)^n$$

Where; p = The probability a tree will die in any one year, ε = Constant death probability and n = year.

If $p = 0.98$ (2 per cent survival) when n = AGEMAX, then;

$$0.98 = 1 - (1 - \varepsilon)^{AGEMAX}$$

$$(1 - \varepsilon)^{AGEMAX} = 0.02$$

Therefore; $\varepsilon = 1 - 0.02^{AGEMAX}$

The application of the basic mortality probability ε in the above equations results in the generation of the probability of mortality p as shown above. The intrinsic survivorship curve generated for a species is in the form of a negative exponential. In the JABOWA model there are two mortality curves that are associated with differing survival probabilities, the annual increment is the trigger for the initiation of the alternative mortality level. Trees with an annual diameter increment of less than 0.01 cm/year are subjected to a second mortality/survivorship curve set such that there is a 1 per cent chance of surviving ten years (the probability a tree will die in any one year = 0.368). Thus, mortality of individual trees is represented by two survivorship curves that are linked by an increment threshold. The JABOWA model and many of its derivatives use similar mortality functions despite the fact that predictions from the original model produced size class distributions (diameter with respect to age) that are noticeably different from conditions recorded from forested environments. The model produces too many stems in the diameter range 10-20 cm. This led Botkin *et al.* to comment at the end of their paper: "If the observations available are in fact representative of New England forest, then perhaps the assumptions regarding mortality require modification". This was also found to be the case in a JABOWA derivative known as FORTNITE (Harrison and Ineson 1987, 1988). Independently, Noble (1987 *pers. comm.*) noted that the diameter distributions held in memory in the computer are not as would be expected or observed in a 'natural' forest system.

One possibility for future research could be to develop functions for mortality that are based on some combination of diameter increment as a ratio of the maximum possible for the species, whilst also including density dependent effects. The aim of this research would be to relate patterns of mortality to ecological processes e.g. intensity of competition and size.

It could be argued that for the purposes of management, modelling mortality could be simplified to routines allowing selective thinning and felling regimes because efficient management aims to minimise mortality. However, an accurate mortality function that reflects ecological reality is required to determine the optimum silvicultural practices. Very little is known about the response of mixed age polyspecific broadleaved woodland to management, and the specific practices that would minimise mortality remain unclear.

1.6.4.2 Regeneration.

The establishment of saplings in the JABOWA model is dependent on a number of conditions that vary for different species. For example to regenerate birch, a certain amount of light needs to be available at the forest floor, also the value of DEGD, the growth limiting factor due to temperature, needs to be between the maximum and minimum for the species. These tests, or switches, act to determine which species will occupy a site. It is assumed that there is a seed source available for all species. The numbers of seedlings produced by the model will be one of the 'drivers' for the stochastic nature of forest dynamics. Establishment and regeneration is also an aspect that can be manipulated by forest managers by planting or preferential selection of certain tree species, and there is considerable scope for the inclusion of managerial manipulation of the regeneration phase within gap-models. The process of natural regeneration is perhaps less well understood than either tree growth or mortality and is correspondingly difficult to model. If forest development is to be predicted for the purposes of management for a predefined period then the modelled regeneration ~~could be directly~~ could be altered to match specific stocking levels. For investigation of 'group system' management by natural regeneration a more ecological approach would be required.

1.7 Size of the modelled area.

The size of the plot that is modelled is very important. Field measurements from the temperate broadleaved forests of north eastern U.S.A. by Runkle (1985) report that only ≈1 per cent of the land area was covered by gaps of an area between 400 and 1490 m^2. A larger area is covered by smaller gaps but this can be quite a variable proportion in different forests. Gaps were caused by the death of dominant trees usually due to lightning strikes or high winds, but disturbance was generally low. Dengler (1939) states that for mixed conifer/hardwood forest in the Balkans small even-aged areas of between 0.01 ha and 0.25 ha are commonly found. The level of gap production due to endogenous disturbance is likely to be similar for 'undisturbed' woodlands in the U.K. There is a distinct lack of data for gap-sizes in the U.K. because unmanaged 'undisturbed' forest is uncommon.

A large modelled area would, in effect, reduce the sensitivity to gap-phase effects because these would be seen on a relatively small proportion of the area at any one time and gap-phase replacement over the total area of the plot would become increasingly unlikely as the plot size increases. A smaller plot size allows simulation of gap-phase effects over a larger proportion of the plot when it occurs. From a theoretical standpoint, the use of a very large plot is tantamount to a reversion to the holistic treatment of forest dynamics. The advantages of large areas have already been discussed and are best modelled by the use of specialised stand or stand class models (sections 1.5.1.-1.5.2.). The choice of a sensible simulated plot size is especially important because no explicit spatial consideration of individual trees (with the exception of height) are used in distance independent gap models.

The general principle should *always* be to match the size of plot to the size of large dominant trees (say about 300 m^2), and the gaps produced by their death, in a given forest type. Botkin *et al.* (1972) however, use a plot size of 10 X 10m as do Aber and Melillo (1978) in the JABOWA derivative FORTNITE. If the size of the gap created by the death of mature trees is considered, a plot size of 0.01 ha is, again, indisputably inadequate.

A logical approach is to match the size of large dominant trees to the size of the modelled plot by consideration of the diameters of the crowns (or canopy areas) for mature individuals of the species involved. A suitable plot size should allow sufficient space for the crown areas of several mature trees. Examination of crown diameter data for broadleaved species commonly found in the U.K. supports the findings of Shugart (1984) shown in Table 1.4. Pryor (1985) studied the relationship between dbh and crown diameter for many broadleaved species at different stocking levels in the U.K. The data were restricted to trees within the diameter range normally expected in productive forestry rotations. Within this range a strong linear relationship existed. However, it is likely that crown diameter would have tended towards an asymptotic value had data been collected from trees of the largest diameters and included in the analyses. Table 1.5 shows the largest crown diameters from the studies by Pryor (*op. cit*) without recourse to (potentially unreliable) extrapolations outside the range of diameters considered in the regression analyses. If the relationship for the full diameter range is indeed asymptotic, and further study would be necessary to establish this, then the predicted values for crown area will not be far from the species maxima.

If a plot size of 0.08 ha were chosen at least two trees would be capable of attaining near maximum size, but if a plot size of 0.01 ha (the size used in the JABOWA and FORTNITE models) no individuals of the species considered in Table 1.5. would be capable of reaching maximum size.

Table 1.4. Results of experiments with different spatial scales for plot size used in a gap models for Appalachian and north-eastern hardwood forests in the U.S.A. (Shugart, 1984).

Plot size ha	Can a dominant tree reach maximum size?	Does gap-phase replacement occur?
0.01	NO	YES
0.02	NO	YES
0.04	YES	YES
0.08	YES	YES
0.2	YES	RARELY
0.4	YES	NO

Table 1.5. Crown diameter, crown area and stem dbh from canopy dominant trees in the U.K., data taken from Pryor (1985).

Species	Stem diameter (cm)	Crown diameter (m)	Crown area (ha)
Quercus robur	98	20	0.0314
Fagus sylvatica	90	19.5	0.0298
Fraxinus excelsior	80	17.5	0.0241
Acer pseudoplatanus	87	18.5	0.0269

The study of gap-phase dynamics includes death and regeneration of trees, and the area disturbed by the death of a large individual should also be considered in the selection of an appropriate plot size. The choice will be a function, not only of the maximum crown area for a tree, but also its maximum height.

It is strongly recommended that the size of modelled plots for growth simulation in U.K. broadleaved forest should be greater than 0.035 ha but not more than 0.2 ha (see Tables 1.4 and

1.5). This is of sufficient size to allow between 1 and 6 trees of maximum size on a simulated plot.

1.8 Development of gap models.

The original JABOWA model has been adapted and extended to simulate different forest environments and for a variety of objectives. Some of the gap models derived from the original JABOWA are more suitable for the objectives of this study than others, and the most suitable will be briefly described, in their published form. In later chapters these models are modified to include results of further research and to improve the quality of the output in accordance with the objectives of this study.

1.8.1 The FORTNITE model.

The authors of the FORTNITE model (Aber and Melillo 1982) regard nitrogen availability as the major limiting element in temperate forest growth. It uses the core of the JABOWA model for the development of trees through time on a 0.01ha plot (see section 1.7.). The dynamics of nitrogen in the forest system are also considered through another 'sub-model' and the two are linked by input from the forest biome in terms of dead litter, and supply of nitrogen to the trees from the decomposition of the litter 'cohorts' over time. Growth in the trees is, in turn, modified by nitrogen availability, and weight loss in the litter cohorts is determined by linear decomposition rates, which ultimately give rise to free nitrogen. Dead tree litter is classified into distinct types that have associated decomposition rates.

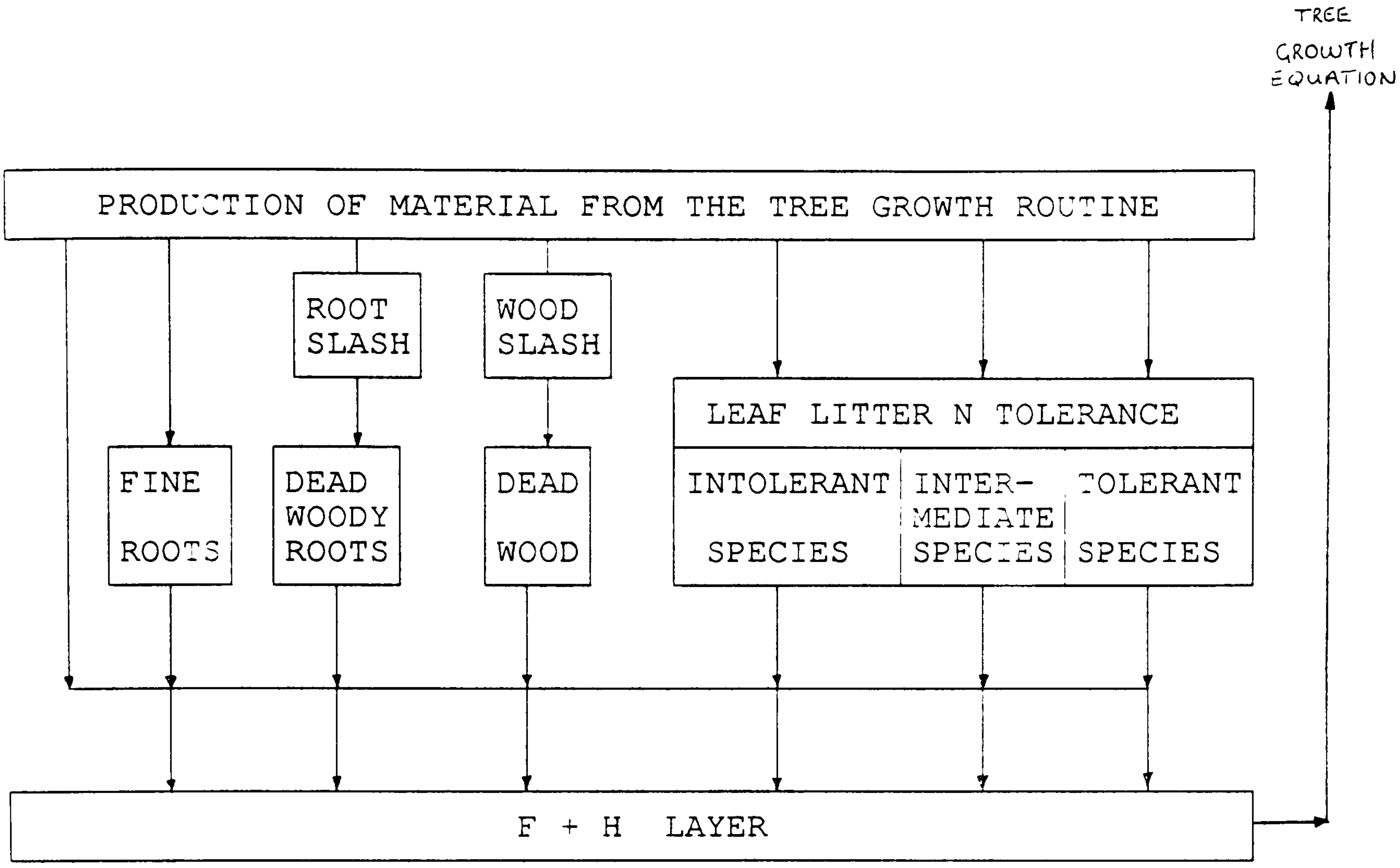
The tree growth algorithm in FORTNITE is largely the same as that described for the JABOWA model but with one very significant difference. The growth equation for diameter increment of trees has been removed and replaced with a constant for the maximum potential diameter increment for an individual, "There is currently no effect of size or age on growth rates" (Aber and Melillo *op. cit*). This is an unacceptable over-simplification of the growth pattern of trees. The model is, however, very detailed in its simulation of nitrogen dynamics.

The model is compartmentalised due to the nature of the data that were available from the study at the Hubbard Brook ecosystem. Each litter compartment has an input rate, an output rate and a present value. Biomass inputs are a function of time as each tree on the simulated plot grows and produces litter, and as individuals die. Leaf biomass, for example has been shown to decompose at very different rates depending upon the tolerance of the species to nitrogen availability (Melillo *et al.* 1982).

The calculation of nitrogen dynamics is based on two major assumptions; (i) As no good data are available on fine root turnover it is assumed by the authors that the turnover of fine roots will be similar to that of the leaves (i.e. dependent on the tolerance of the species to nitrogen availability). The reasoning behind this assumption is that both roots and leaves are neither supportive nor transportive and both are 'ephemeral resource gathering tissues', but there is no evidence to suggest that root and leaf degradation are related. (ii) The amount of fine root tissue is assumed to be related to the root/shoot ratios measured for different species (Bormann and Likens 1979). Fine roots are a very important component in the dynamics of nitrogen and are likely greatly to affect tree growth. It also likely that trees under nutrient stress will divert more of their resources into fine roots, at the expense of woody biomass, and this would encourage higher rates of root litter turnover (McClaugherty *et al.* 1982). Thus fine root turnover is likely to be a highly variable factor.

Woody root biomass in the model is taken from the ratio described by Whittaker (1974). Below ground biomass is equal to 20 per cent of above ground biomass, 32.8 per cent of the resultant below ground biomass is assumed to be woody and, as such, to decompose twice as fast as above-ground woody litter. One main simplification is the correlation of weight loss of different categories of tree litter to nitrogen immobilisation and mineralisation into the F and H layer of the soil.

Litter is classified into leaves, fine roots, woody roots, twigs, and ten size classes of large woody litter. Leaves, fine roots and twigs have decomposition dynamics within the model that use lignin and nitrogen content derived from field measurements.



Adapted from Melillo et al. (1982)

Figure 1.4. Flow diagram of the nutrient decomposition module of the FORTNITE model. The availability of Nitrogen will 'feedback' to influence individual tree growth.

$$K = 0.79 - 0.03(L:N) \quad \text{(Melillo \textit{et al.} 1982)}$$

Where K = percent weight loss, L = initial percentage of lignin and N = initial percentage of nitrogen. Weight loss (i.e. decomposition) in large woody litter is related to the mean diameter of the litter size class (ten classes with 10 cm diameter size increments).

$$K = 0.13 - 0.014 \times DIAM$$

As the weight of a cohort declines the nitrogen concentration within the cohort will increase until it reaches the point where net mineralisation will begin (around 2 per cent nitrogen by weight) and at this point the remaining weight and nitrogen is transferred to the F and H layer compartment. Each year may produce a series of new litter cohorts to be modelled over successive years. Nitrogen mineralisation takes place from the F and H layer in proportion to weight loss. This is a constant 9.6 per cent per year multiplied by a function to increase decomposition under low leaf area canopies, an effect often observed after clear cutting. Thus nitrogen availability is equal to the total mineralised from the F and H layer, minus the immobilisation demands of the current litter cohorts plus a constant 5 kg/ha from aerosols or precipitation and 10 kg/ha from mineralisation from the mineral soil. These values could be altered for U.K. values in any future modification.

The concept of modelling the dynamics of nitrogen in relation to the growth of trees is only meaningful if the relationships between nitrogen availability and relative growth rates are known for the species being studied. Work by Mitchell and Chandler (1939) forms the basis of the relationship used in the FORTNITE model. They developed species specific relationships between available nitrogen and foliar nitrogen concentrations. They classed the results in relation to the tolerance of individual species to nitrogen availability. Tolerant species grow well under conditions of low nitrogen availability, but cannot respond to high availability with greatly increased growth. Conversely intolerant species cannot survive in conditions of low nitrogen availability but growth rate will increase with increasing nitrogen availability.

The work by Aber *et al.* (1979) relates the relative nitrogen availability, derived from the earlier work of Mitchell and Chandler, to the absolute nitrogen availability. The relative nitrogen availability is obtained from the absolute nitrogen availability as predicted by the forest floor component of the FORTNITE model, using the following equation:

$$MC = -170 + N(4.0)$$

Where MC = net nitrogen availability on the Mitchell and Chandler scale and N = the net nitrogen availability in kg/ha/yr. The relative nitrogen availability is then converted to a relative growth factor depending upon the nitrogen tolerance of the species. Species can be classified as tolerant, intolerant and intermediate.

The advantage of this model is that it can show how the nitrogen status of the forest can change over time, especially with regard to management practices. For example, the authors of the model use it to investigate the effects (both long and short-term) of differing harvesting techniques i.e. whole tree harvesting, removal of above-ground biomass including foliage and 'normal' harvesting, where the foliage is allowed to remain on site. The model predicts levels of nitrogen throughout the rotation that, according to the authors, resemble field measurement.

The FORTNITE model has removed the constraint on maximum biomass used in the JABOWA model for simulating an unspecified nutrient becoming limiting to tree growth. This growth limiting multiplier has been replaced by the nitrogen dynamics model. The obvious advantage of this is that predicted biomass output is independent of the parameters used to drive the model. However, the nitrogen dynamics of the model is very sensitive to the values predicted in the tree growth model for total leaf production. This is because the leaf production also determines the fine root production (see assumptions section 1.8.1), and these two together form the main nitrogen input to the forest floor litter (but tree growth is modelled very inaccurately). The model has been used to predict nitrogen availability under differing management regimes for example, differing rotation lengths and differing harvesting methods in terms of biomass removed from the site. It was found that successive short rotations reduced the total leaf and fine root biomass being returned to the forest floor. The consequence was reduced nitrogen availability and thus reduced yields in successive rotations. The model can be used to simulate differing silvicultural management, times of fellings, species to be felled (or thinned), and diameter limits on felling can be specified. The effect of removing species can be predicted. For example, only allowing nitrogen tolerant species to remain will reduce nitrogen availability due to slower growth and longer times for decomposition of leaf litter from tolerant species. One of the limitations to the model at the time of publishing in 1982 was associated with its use on sites with low nitrogen availability where fertilizer nitrogen had been applied. The model is not suitable for this because nitrogen retention times in the forest floor litter, and storage by trees are not well known.

The main weaknesses associated with the model are; (i) the removal of the growth pattern for the diameter increment of individual trees, potential tree increment is assumed constant irrespective of tree size. (ii) Complex modelling of nitrogen dynamics depends on many factors related to tree growth, with intricate, not fully substantiated, feedback to the growth of trees. (iii) More site specific data is required than for its predecessor, and (iv) the detailed modelling of the nitrogen dynamics assumes N to be the most important resource, besides light, influencing growth, this may not be so for all woodlands.

The FORTNITE model has been adapted for simulations of woodland development at Meathop wood in Cumbria (Harrison and Ineson 1987, 1988). This woodland has been much studied and a large amount of data exist, dating back as far as 1939, when the wood was last coppiced (with the exception of some oak standards). The modified FORTNITE model was used to simulate woodland development starting from the known woodland structure in 1939, and the predicted output for the years 1962-1972 (the period of the detailed IBP measurements) were compared to field data. The modifications made by Harrison and Ineson (*op. cit.*) do not alter the biological relationships described in the original program (Aber and Melillo 1982), with the exception of tree height-diameter equations. Problems with the generation of the random numbers used in the model with regard to anomalies experienced when a management cut is included in the model were noted and rectified. Management options to allow selective felling and thinning as well as coppice regrowth have been included. A major problem is that of the small plot size compared to the crown area of mature trees (section 1.7.).

In summary, the nitrogen availability due to decomposition is modelled with a great degree of detail, however the pattern of growth by the individual trees, upon which this feedback effect is mediated, is oversimplified to an unacceptable extent. More understanding and testing of models that concentrate on tree growth to a greater degree is required. *A comprehensive understanding of the basic relationships between regeneration, growth and mortality is required* and should be expressed in gap-models that consider soil parameters in a simple form. Once this has been achieved the wider implications of the effect of soil parameters on mixed age polyspecific woodland can be attempted. The use of the FORET model for simulating forest dynamics is a more suitable starting point.

1.8.2 The FORET model.

The FORET model by Shugart and West (1977) is another forest growth simulator that uses the basis of the JABOWA model for the growth of individual trees on a plot. One of the main aims behind the research in this model was to be able to assess the impact of the Chestnut blight disease (*Endothia parasitica*) on the forests in the Appalachian mountains of the eastern USA. Circular plots of 0.0833 ha were used, in contrast to the square 0.01 ha plots in the original JABOWA model. Since spatial components are not specifically defined within gap-models the shape of the plot can only refer to the inventory data against which such models are verified and validated. Shugart (1984) regards plot size, as previously indicated, to be very important when modelling gap-phase replacements (see Table 1.4.). Some of the subroutines of the original JABOWA model were altered to allow for modifications. One such modification was the inclusion of a subroutine that allows certain species of tree to sprout coppice shoots when the stems are cut. Shugart and West noted that vegetative sprouting can be the dominant form of reproduction in the Appalachian forests, for particular sizes and species of trees. The computer model selects eligible stumps and regenerates a tree as a sapling in place of the tree that has been killed in the mortality routine. Only a few of these trees are 'allowed' to sprout new shoots. Were this model to be adapted for use in the U.K. for coppice management, the sprouting routine would need to be altered to predict accurate levels of sprouting for a stand of cut-over stems. Each stump would need the facility to develop multiple shoots and growth in the early stages of shoot development may require enhancement due to the remaining well-developed root system.

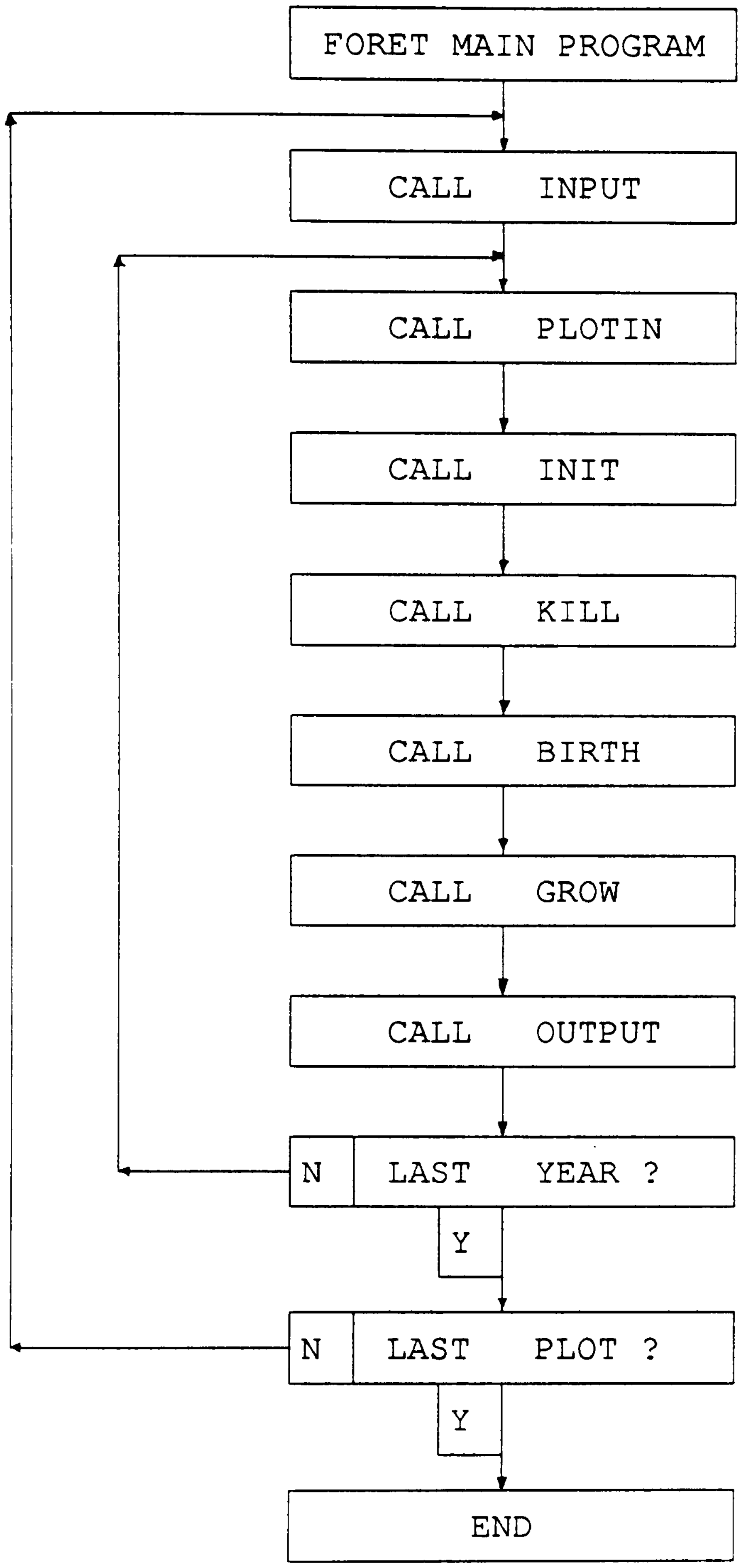


Figure 1.5. A simplified flow diagram of the FORET model, this basic structure applies to modifications made to FORET that are discussed in Chapter 4.

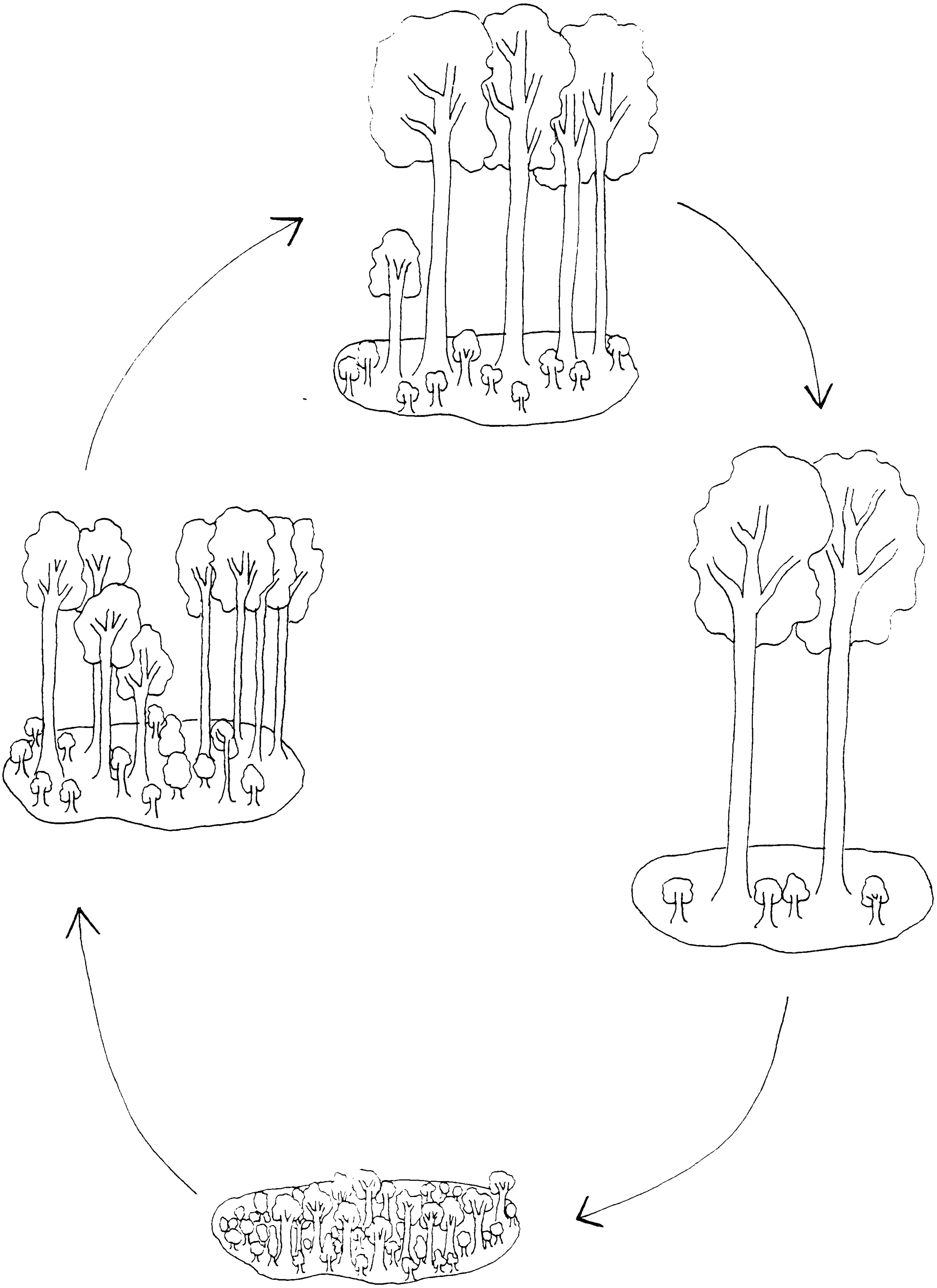


Figure 1.6. A diagrammatic representation of dynamic processes within a small area of forest that a gap-model, such as FORET, can simulate.

The prediction of height based on diameter would need investigation and any volume predictions for small dimensioned coppice would require inclusion. Whilst these are relatively trivial points in a model directed towards the prediction of species change, they are of great importance if the model is to have a management application.

Another modification to the JABOWA model by Shugart and West (*op. cit.*) was the inclusion of the capability to deal with a greater number of tree species. However, consideration of soil water availability was removed and this restricts the application of the model to lower slope positions where light availability and not water availability is the limiting factor. The regeneration of trees into the forest plot is modelled by a subroutine known as 'birth' that works along similar principles to that of the JABOWA model. For each species a series of yes/no (0 and 1 respectively) questions must have the correct value in order for a species to be eligible for regeneration.

No attempt is made at nutrient modelling in the original FORET model but Shugart (1984) reports that Weinstein (1982) has adapted FORET to produce a model called FORNUT that models nutrient dynamics in similar sort of way to that of Aber and Melillo (1982) i.e., relating nutrient availability to a tree growth modifying factor.

The FORET model was used to compare simulations of forest development in the Appalachian mountains with the present species assemblage and compare it with similar simulations that contain the Chestnut species (*Castaena dentata*). A simulation of forest development was carried out where the chestnut was removed (to simulate the blight) half way through. The authors state that the model simulated species structure of the present forests well, and also corresponded to the data available for the pre-blight forests. However, the data for verification of the pre-blight forests comes from scant quantitative sources, and mainly from qualitative descriptions and a knowledge of the volumes of species removed in logging in the pre-blight forests at the turn of the century. The main differences between the pre-blight forests containing chestnut, and the Appalachian forests of present times predicted by the model was greater leaf area and above ground biomass with the chestnut. But the number of stems per unit area before and after the blight remains more or less the same. The FORET model has also been used to project the influence of air pollution on stand development (West *et al.* 1980) and to simulate successfully forest development for a mixed pine-hardwood forest in Arkansas (Mielke *et al.* 1978).

1.9 Summary and research recommendations.

The individual-tree models summarised in sections 1.8.1 and 1.8.2 have the potential for modification to allow them to be used for the prediction of the effects of management strategies. There are numerous techniques used in the development of such forest models that will require modification to facilitate the production of useful and accurate results. Some of these are specified below.

The basic growth equation, which has remained unaltered in many of the JABOWA derivatives, requires modification. The fundamental relationship for diameter increment is based on a height-diameter relationship. This is assumed to be parabolic for all species, and is set for a species from trees of record dimensions (ie. exceptionally large trees) found in natural stands. Unfortunately large trees from natural stands are now rare (if not nonexistent) and data are almost impossible to obtain in the U.K. The nature of the relationships between height and diameter should be established for species commonly used in the U.K.

The basic growth equation is modified by a series of growth multipliers designed to represent the decrease in growth rate due to sub-optimum environmental conditions. Light availability may be the most significant of these or, perhaps, competition for space/soil resources. These are of importance since management can manipulate their significance in influencing tree growth within a stand, they are also a non-Cartesian representation of the spatial relationships between trees on a plot. The temperature limits for a species are of restricted usefulness for management since tree species selected for management may be assumed to be matched to the site under consideration.

The diameter distribution of individuals 'grown' in the computer should match those collected from field measurement. This has not been the case and has been reported by Botkin *et al.* (1972), Aber and Melillo (1982) and Harrison and Ineson (1988). This problem requires *the* *matching of the interactions between the processes of growth, regeneration and mortality* within the model.

The processes of mortality and natural regeneration require additional modification in order to cope with the possibilities of planting, and the determination of optimum stocking levels. A reliable mortality function is required to investigate the optimum silvicultural practices with respect to the objectives of management.

However, of overriding importance is the general alteration of suitable models for U.K. conditions. The modified models will require extensive verification and validation before application to woodland management is possible.

CHAPTER 2. Formulation of modified gap model growth equations.

2.1 General forms of growth equations.

A useful growth equation should express the geometric features that are logically expected. For example, values should range from zero at the beginning of tree growth and reach an asymptotic value for mature individual trees or stands. An inflexion is also to be expected, but the growth curve should not be symmetrical about this point, faster growth being anticipated in the earlier phases. Simple regression techniques that construct growth and yield functions from observed data may not include such features, although past experience and application of logical thought may indicate their occurrence.

Perhaps the most notable contribution to the quantitative expression of growth processes is the Chapman-Richards generalisation of von Bertalanffy's growth equation (Pienaar and Turnbull 1973). Growth rate is expressed in terms of the difference between anabolic and catabolic metabolism of an organism. von Bertalanffy formulated a hypothesis that the anabolic rate of an organism is proportional to its surface area through an allometric relationship, whilst the catabolic rate is proportional to the volume of the biomass. The allometric constant, from studies on a wide variety of terrestrial and aquatic organisms, was thought by von Bertalanffy to be 2/3. The basic growth equation was expressed;

$$\frac{dV}{dt} = \eta V^{2/3} - \gamma V$$

where dV/dt is the volume growth rate and V the biomass volume, η and γ are variable parameters (von Bertalanffy 1951). Independent work by Chapman (1961) and Richards (1959) on fish and plant growth respectively, argued that the constant of allometry defined by von Bertalanffy was too inflexible and not applicable to many forms of life. The modification to the original equation is known as the Chapman-Richards equation, being identical to that of von Bertalanffy but allowing a variable constant of allometry to be determined for different organisms (or, more usually, groups of organisms); where M = the constant of allometry.

$$\frac{dV}{dt} = \eta V^{M} - \gamma V$$

Integration of this equation can establish the yield at any given time by application of Bernoulli's equation for the integration of differential equations von Bertalanffy produced;

$$V = b_1[\ 1 - e^{b_2(t - b_4)}]^{b_3}$$

The general form of the Chapman-Richards equation has the allometric constant 2/3 replaced by a variable parameter b_3 (Pienaar and Turnbull 1973). If the model were applied to stand growth; V = the volume at time 't', b_1 represents the maximum volume per hectare that can be attained on the site, b_2 controls the general shape of the curve, b_3 shortens or lengthens the time required for the curve to culminate, and b_4 is a scaling value. Munro (1984) notes that an interesting property of this equation, when applied to tree growth, is that maximum current annual increment (CAI) can be shown to occur at a time (age);

$$\frac{b_2}{ln|\ b_3\ |}$$

The Chapman-Richards growth equation can be applied to the growth of individual trees or to stands. For individual trees the rate of biomass growth, for example, can be approximated by the net difference between anabolic and catabolic processes. Anabolic metabolism is assumed to be directly proportional to the photosynthetic area of the tree. An allometric relationship commonly used for tree growth is that of dbh to crown diameter or leaf weight. Catabolic processes are assumed to be proportional to the total biomass of the individual.

2.2 The relationship between growth and yield.

There is a functional relationship between growth and yield in a forest environment. Yield is often of primary concern to the forest manager and is expressed in terms of total wood volume (or biomass) produced at the end of a defined period of time e.g. a rotation or a thinning cycle. Growth is the increase in size (volume/biomass) over a given period of time. Both of these concepts can be applied to stands or individual trees (involving area considerations for describing stands). Common units of growth and yield used in the study of forest development are:-

Growth: m^3/ha/yr (for stands), m^3/yr or cm dbh/yr (for individual trees)

Yield: m^3/ha (for stands), m^3 (for individual trees)

Clutter (1963) was amongst the first to realise and apply the obvious relationship between the two and emphasised that integrating a growth function should generate a yield function, (the logical antithesis being to differentiate and produce a growth function from a yield function). Earlier work often considered the two concepts separately and compatible growth and yield functions were not previously investigated.

Vanclay (1983) argues that for mixed forests "models which express the status of the forest at some future time are termed yield models, and those which express increment are termed growth models". Although this classification is theoretically correct, is it neither useful nor definitive.

Individual tree models have, on the whole, been developed in order to cope with the problems of mixed ages and species of trees growing together in close proximity. A model simulating individual tree growth can also produce yield estimates by simply summing each individual period of modelled growth. This is the empirical equivalent of integrating the growth equation. Similarly the summation of growth or yields of individuals can generate estimates for stands (by consideration of the area of the plot). Thus the distinction made above is not easily applied, except to descriptions of the equations alone. However, growth functions provide far greater flexibility than yield functions. Summing the modelled growth allows greater scope to alter the management regime or to cope with altered environmental conditions that affect growth, whilst the yield equation cannot cope with comparable variations.

2.3 Formulation of the original JABOWA growth equation.

The growth function used in JABOWA-type gap models is analogous to the Chapman-Richards growth function. It assumes that the rate of growth is equal to a constant multiplied by the leaf area of the tree (anabolic processes), which is multiplied by a factor representing the size of the tree relative to the maximum possible (catabolic processes). Thus as a tree approaches its maximum size the growth rate is progressively reduced, until growth stops at maximum size. This simulates the greater proportion of photosynthates required for maintenance in preference to growth as size increases (Harper 1977), and as increasing inefficiency of transport of water, nutrients and the products of photosynthesis due to aging occurs (Spurr and Barnes 1973, 1980).

The basic growth equation for an individual tree is expressed as:-

$$\frac{d(D^2H)}{dt} = R.LA\left(1 - \frac{D.H}{D_m.H_m}\right)$$

Where; R is a constant, LA = leaf area, D = diameter at breast height, and H = height. D_m and H_m are the species maximum diameter and height values. Rate of growth is described in terms of volume increment in a one year interval ($d(D^2H)$).

"The height of a tree with a dbh D (in cm) is assumed to be given from the following expression (Ker and Smith 1955):

$H = 137 + b_2D - b_3D^2$ " (Botkin *et al.* 1972)

Note; 137 cm is the U.S. conventional breast height in centimetres (130 cm is the U.K. convention).

b^2 and b^3 are chosen such that $H = H_m$ and $\frac{dH}{dD} = 0$, when $D = D_m$

$$\frac{dH}{dD} = b_2 - 2b_3.D_m$$

Therefore; $b_2 = 2b_3.D_m$

and $b_3 = \frac{b_2}{2D_m}$

Substituting;

$$H_m = 137 + (2b_3.D_m).D - b_3D^2_m$$

$$b_3 = \frac{(H_m - 137)}{D^2_m}$$

Similarly, by substitution;

$$b_2 = \frac{2.(H_m - 137)}{D_m}$$

The species specific parameters b_2 and b_3 relating diameter to height are determined from the two simple parameters of maximum height and diameter. These parameters are based on the dimensions of 'record' trees for a given species (refer to section 3.6.1).

It is assumed that the ratio between basal area and the leaf weight of the tree remains constant for the life of the tree and that leaf area is directly proportional to leaf weight.

Thus for a species $_i$ leaf weight = $C_i.D^2$, (Perry *et al.* 1969). Because leaf area and leaf weight are proportionally related, the constants $R.C_i = G$. The central growth equation becomes;

$$\frac{d(D^2H)}{dt} = G.D^2 \left(1 - \frac{D.H}{D_m.H_m} \right)$$

Substituting and differentiating; $H = 137 + b_2D - b_3D^2$

$$\frac{dD}{dt} = \frac{G.D \left(1 - \frac{D.H}{D_m.H_m} \right)}{274 + 3b_2D - 4b_3D^2}$$

The growth rate constant is scaled such that the equation will represent the maximum growth rate possible for the species.

2.4 Modification of the growth equation.

The basic growth equation in the JABOWA model is set such that the maximum height and diameters attainable by a particular tree species are based on individual forest trees of 'record' dimensions. These data, and an estimate of maximum age for each species, are then used to derive not only the height-diameter relationship for the species, but also the growth rate constant (see Chapter 3).

In order that a JABOWA type gap-model may be used for the purposes of simulating forest management practices in the U.K. it is essential to establish a growth equation that will produce predictions that fit, as closely as possible, observed growth data.

2.5 Record tree data.

Data for large trees that have developed within a closed forest environment in Britain are remarkably scarce, and notable trees of large dimensions are usually long-lived, open-grown specimens or ancient pollards (Mitchell and Hallet 1985). *Trees of this type are unsuitable for the basis of any species specific height-diameter relationship.* Record trees from the United States may be more representative of their species since the majority have been recorded from natural stands (Harlow and Harrar 1969), and as such may be a better approximation of the maximum dimensions possible for individuals of a species in near optimum growth conditions. The equations used in the original model take no account of the variability of the height-diameter relationship in their derivation.

2.6 Use of existing published yield tables.

The average tree dimensions from the highest yield classes or plantations of different commonly grown species (Hamilton and Christie 1971) *cannot* be used to derive height-diameter relationships based on diameter for individual trees, since the published figures have been derived using height as the independent variable. Yield tables are constructed by making use of the volume-top height relationship that is assumed to occur irrespective of rate of height growth (Hummel 1955, Hummel and Christie 1957). The growth curves representing different yield classes are constrained to pass through predetermined 'representative' points in an empirical manner by application of orthogonal polynomials. Relationships between height and diameter are determined by parabolic or logarithmic functions using *height* as the independent variable, for a predetermined management procedure. Height can only be used as an independent variable if height growth remains vigorous. This is not the case for many broadleaved species where height growth declines or ceases well before diameter increment slows. For computer simulation of management practices using broadleaved species over long rotations (e.g.sawlog or veneer production) diameter is the preferred choice of independent variable for the construction of a height-diameter relationship. The relationships in the current gap models use *diameter* as the basis for height prediction.

General relationships between height and diameter used in construction of U.K. yield tables are:

$$D = a + bH + cH^2 \quad (1)$$

$$LnD = a + bH + cH^2 \quad (2)$$

Where; D = Diameter at breast height, H = top height, and a, b and c are constants. Equation (1) is used for Corsican pine, logepole pine, European larch, Japanese larch, western hemlock, grand fir, noble fir, sycamore, ash, birch, and poplar. Equation (2) is used for Scots pine, Sitka spruce, Norway spruce, Douglas fir, and western red cedar. The relationship between height and diameter is derived for each yield class in oak and beech whereas all the above species are characterized by equation 1 or 2 for all yield classes (Christie 1972).

2.7 Height-diameter relationships for broadleaved species.

One objective of this study was to manipulate existing individual tree gap models so that they may be used for simulating management practices in the U.K. It was therefore necessary to derive height-diameter relationships from data recorded from managed and semi-natural stands.

2.7.1 Summary of height-diameter studies.

A number of height-diameter equations were compared for oak, beech, ash, sycamore and birch. They are based on data from a wide range of sites in the U.K. and from plots in the Netherlands. The results were assessed by the use of the Furnival index, an examination of the residuals and consideration of the biological interpretations that could be applied to the equations. It was found that several curves can adequately describe the relationship for diameters exceeding all but those of the very smallest of trees. However, for the purposes of individual tree models where predicted values for height are required for all values of diameter, the choice of suitable curves is more limited.

2.7.2 Introduction to height-diameter relationships.

The purpose of deriving a height-diameter curve is to arrive at a fair average height for *any* diameter. Chapman and Demeritt (1936) remark; "Curves of height on diameter do not represent a definite biological relationship such as height on age or diameter on age". However, height would be expected to increase with diameter, since increased diameter implies tree growth, and this in turn implies height growth (except in the case of crown death in very old trees). Therefore, curves of height with respect to diameter should normally show an increase in height, however small, with increasing diameter.

In any investigation of height-diameter relationships there is likely to be considerable heterogeneity in the data collected, and it is usual that measurements of trees, taken from stands containing differing age classes and embracing a variety of sites, will show a wide range of heights for the same diameter. Stands of trees of similar age but of different stocking levels (on similar sites) may be of a similar height, but are commonly of greatly differing average diameters. It is, nevertheless, possible to determine good relationships between height and diameter.

Jeffers (1959) and Curtis (1967) recognised that there are many equations that may be used to describe height-diameter relationships. Curtis, in his research on Douglas fir, used all the equations in the analyses presented here. However, unlike the study by Curtis, the data have been combined from many different sites and stocking levels in an attempt to include as much variability as possible, and hence ascertain curves that represent a wider variety of conditions.

2.7.3 Methodology for height-diameter studies.

The data for deriving height-diameter relationships for each of the oak species (*Quercus robur* and *Q. petraea* combined), ash (*Fraxinus excelsior*), beech (*Fagus sylvatica*), birch (*Betula pendula* and *Betula pubescens* combined) and sycamore (*Acer pseudoplatanus*), were collected from areas of woodland in the south of England (Bagley, Wytham, and Tubney woods (Oxon), Savernake forest (Wilts), the Forest of Dean (Glos) and Catmore farm (Berks)). Trees were sampled from many different stand types and at different stages of growth over the widest possible range of diameters. Height measurements were made with a Suunto clinometer, and diameter at breast height (130cm) with a conventional diameter tape. Measurements of diameter were taken to the nearest centimetre, to provide replicate sample observations at integer values along the X-axis (diameter). This allowed estimation and goodness of fit in the regression analyses to be separated, any errors in the measurement of diameter are likely to be small in comparison to the errors in the measurement of height. Data collected by other workers were also used. Crockford *et al.* (1987a) measured many woodland plots from sites all over the UK, and data for all these species, and from research plots in the Netherlands (Wageningen) were also made available.

The method of sampling at each woodland site consisted of transects in a direction chosen at random. Trees occurring on the edges of blocks of woodland were not included in the measurements. Of the data from other sources the data from Crockford *et al., op. cit.* provides measurements for leading trees only, on 10 x 10 m plots. However, plots were sampled from a wide range of woodland types in many stages of development, the Wageningen data was a complete inventory from fairly uniform research plots for each species. These other sources of data represent approximately 20 per cent of the total number of trees measured for each species.

Oak data were separated into two classifications of 'standards' collected from coppice with standards woodlands and from widely-spaced stands of trees, and 'high forest' oak collected from trees grown at closer spacing. Data for each of the other species were combined for the regression analyses. The total number of paired observations used for each species were; ash 123, beech 175, birch 410, sycamore 316 and oak 1313 (divided into 777 widely-spaced 'standards', and 563 'high forest' oaks).

Table 2.1. Equations used in the analysis of height diameter data.

---

1. $H = a + bD + cD^2$
2. $H = 130 + bD + cD^2$
3. $H = a + bD^{-1} + c D^{-2}$
4. $H = 130 + bD^{-1} + c D^{-2}$
5. $H = a + b\mathit{Log}D$
6. $H = 130 + b\mathit{Log}D$
7. $\mathit{Log}H = a + b\mathit{Log}D^{-1}$
8. $\mathit{Log}(H - 130) = a + b\mathit{Log}D^{-1}$
9. $\mathit{Log}H = a + b\mathit{Log}D$
10. $\mathit{Log}(H - 130) = a + b\mathit{Log}D$
11. $\mathit{Log}(H - 130) = a + b\mathit{Log}D + c(\mathit{Log}D)^2$

Where H = height, D = diameter. The coefficients a, b, and c were determined by regression.

All of the equations shown in Table 2.1 were fitted to the data for the different species using regression software initially on STATGRAPHICS version 2.6 with verification of all regression coefficients and statistical analyses using MINITAB version 6.1.1. The analyses presented here are for the combined data sets, although each data set had been individually analysed in a manner identical to that presented. All logarithms used are common (base 10) logarithms.

The most appropriate height-diameter relationship for use in the individual-tree growth models was selected by consideration of several criteria;

- (i) Furnival indices.
- (ii) Distribution of the residuals.
- (iii) Coefficients of determination (R^2), where appropriate.
- (iv) Mathematical properties/theoretical and biological implications of the equation.

The Furnival index is based on the concept of relative likelihoods from least squares estimates and, "has the advantage of reflecting both size of the residuals and possible departures from linearity, normality, and homoscedacity" (Furnival 1961). It is used for comparing fitted regression equations when the data for the dependent variable have been transformed (equation numbers 7-11 in Table 2.1), against fitted equations where the data for the dependent variable remain untransformed (equation numbers 1-6 in Table 2.1). For a regression fit with an untransformed dependent variable the Furnival index is equal to the standard error. The lower the value of the index, the better the fit of the equation to the data. Regressions in which the same dependent variable has been subject to different transformations cannot be compared directly for goodness of fit using the R^2 coefficient (Alder 1980). Regression equations that make use of the logarithmic transformation of the dependent variable (Equations 7-11 in Table 2.1) are subject to a systematic bias (underestimation). This can be rectified by the application of a correction factor (Meyer 1944).

The general form (f(D) = a function of D) of the transformed equations (7-11) is;

$$Log_{10}H = f(D)$$

With the inclusion of the correction factor 'C' this becomes;

$$H = C.10^{(f(D))}$$

where;

$$C = 10^{(1.1512.s^2)}$$

and s is the residual standard deviation from the regression analysis (Meyer *op. cit*). However, Alder (*op. cit*) states "when the degree of fit obtained is high (ie R^2 over about 0.9) the various arguments about alternative fitting methods, error distributions etc., are essentially academic".

2.7.4 The effect of management on the height of oak.

Relatively high stocking levels and timely thinnings are stated by Zobel and van Buijtenen (1989) to be necessary for maximum height development of hardwoods like oaks which tend to produce rounded tops with large, heavy branches, if open grown. Pranjic (1970) studied the height growth of oak (*Q. robur*) in Yugoslavia for a variety of sites and management conditions and concluded that the form of height curves for the same forest community is largely influenced by the system of management, and that height development is not always a reliable indicator of site quality. In this way, oak differs considerably from many other species, where it has been found, and generally assumed in the production of yield tables, that height growth is relatively independent of spacing and competition during the productive lifetime of a crop (Evert 1971).

Studies of height-diameter relationships in the U.K. show marked differences for stands of oak grown on a variety of sites under either coppice-with-standards or high forest management. Coppice-with-standards management produces trees of a maximum height that barely reaches the minimum of those grown as high forest for a given diameter (Table 2.2). Figure 2.1 shows scatterplots of data collected from high forest and coppice-with-standards sites with similar soil and drainage characteristics.

Assuming that the sites sampled for each type of crop do indeed cover comparable environmental and soil conditions, it can, for example, be seen that trees in the 60-79 cm dbh size group had an average height of 27.3 m in high forest and only 16.5 m in coppice-with-standards, a difference of approximately 40 per cent in height.

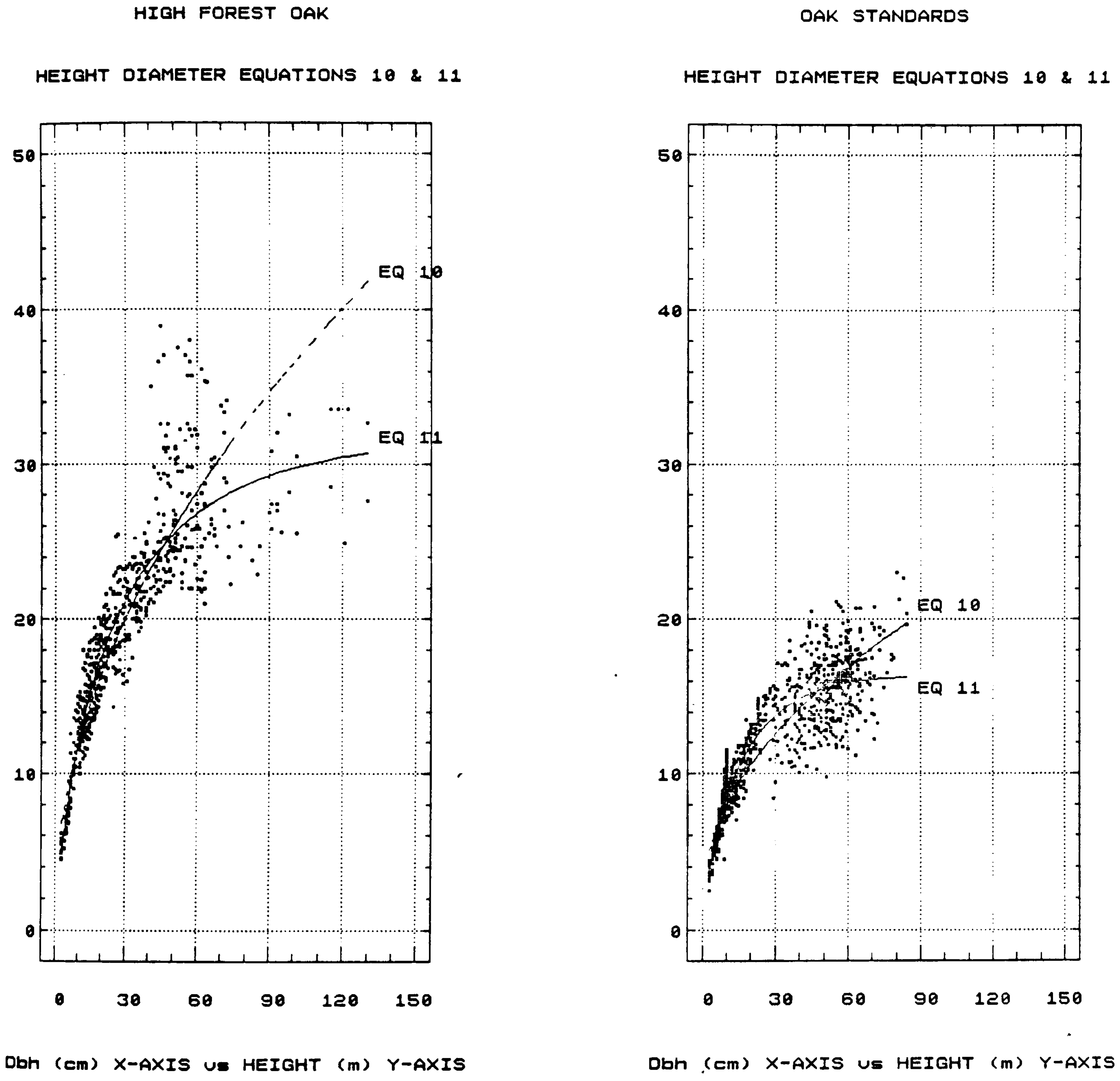


Figure 2.1. Scatterplots of height-diameter data for oak (*Q. robur* and *Q. petraea* combined) categorised as either 'high forest' or 'standards' by the form of management in the stand from which the measurements were taken. Fitted curves 10 and 11 are shown for both.

Table 2.2. Mean values for heights (in metres) with their standard deviations for diameter size group ranges of high forest and coppice-with-standards oak trees.

dbh range (cm)	High forest oak Mean height	 S.D.	Coppice-with-standards Mean height	 S.D.
0-19	13.04	3.54	8.23	2.31
20-39	20.20	2.47	13.63	1.85
40-59	26.59	4.24	15.37	2.19
60-79	27.34	3.98	16.48	2.09
80 +	28.44	3.37	21.40	1.27

2.7.5 Comparison of fitted height-diameter equations.

Most of the equations can be discussed in pairs since they are essentially of the same form but with different intercepts on the Y-axis. The constant ,130, represents zero diameter for a tree with a total height equal to breast height. The values for the Furnival Index and the coefficient of determination, R^2, are presented for each species in Table 2.4.

Table 2.3. Values of maximum tree diameter (in centimetres) and height (in metres) predicted from the fitted equations 1 and 2 in Table 2.1. Maximum diameter occurs at $D = -b/2c$ where c is less than zero.

Species	Equation 1 $H = a + bD + cD^2$ diameter	 height	Equation 2 $H = 130 + bD + cD^2$ diameter	 height
oak (high forest)	86.26	29.83	76.49	31.29
oak (standards)	67.12	16.56	54.06	16.65
ash	43.08	16.61	65.67	26.36
beech	129.4	35.20	103.5	46.15
birch	44.50	21.15	39.11	21.03
sycamore	53.53	24.39	43.99	23.57

Equation 1 and 2 (Table 2.1) give reasonable performance against the statistical criteria, and always produce relatively low values for the Furnival index and high values for R^2. The residuals for these equations often show no pattern in the distribution or magnitude of the deviations from the fitted regression lines. Equation 1 has no constraint on the lower end of the curve and, in accordance with Curtis' (*op. cit*) findings, unreasonable estimates for small trees occurred. Fitted curves for equation 2 are shown in Figure 2.2 for beech and sycamore. It can be seen that the predicted values for height reach a maximum and then decline within the normal range of diameters for all the species considered (Table 2.3.). This is clearly an unrealistic characteristic for a height-diameter equation. Curtis (*op. cit*) remarks; "Trorey (1932) and Ker and Smith (1955)...suggested that heights be assumed constant for diameters greater than that corresponding to the maximum of the fitted curve. However, this implies that the relationship is better represented by some other equation".

Alternatively, the coefficients for an equation of this form could be generated from the height-diameter measurements of a single tree using formulae shown in section 2.3, and without using regression analysis. This is the method used by Botkin *et al.* (*op. cit*) and several derivatives of the JABOWA model.

If these coefficients are taken from record tree data from the U.K. very poor fits are produced, when plotted against measured data (section 3.6-3.6.1) because, as already mentioned, record trees in the U.K. are, almost without exception, open-grown specimens. If these parameters are calculated from the largest trees for each species found in the measured data sets, a more realistic curve is produced. However, height is assumed to reach a maximum at the corresponding diameter and then declines with any further increase in diameter. Although some very large trees have been sampled in the course of data collection, it is unlikely that the largest of these represent a biological maximum for the species.

Equations 3 and 4 (Table 2.1) occasionally gave good fits but the distributions of residuals, especially in Equation 4, often revealed patterns in the data not accounted for by the fitted curve. The fitted curves reach an asymptote, but Equation 3 produced negative values for height when diameters are small. Constraining this form of curve to pass through the natural origin for diameter in Equation 4 considerably worsens the fit. This, coupled with poor R^2 values and large values for the Furnival index (Table 2.4), indicates that these equations are seldom suitable.

Equations 5 and 6 both have the advantage of tending towards an asymptotic value for height with increasing diameter. This is a desirable characteristic for a height-diameter equation, in that

Table 2.4. Values of the Furnival index and the coeffeicients of determination (R^2) for oak, beech, ash, birch, and sycamore. HF denotes 'high forest' oak, S denotes oak 'standards' (see full definitions in the text).

	Equation	oak (HF)		oak (S)		beech		ash		birch		sycamore	
		R^2	F	R^2	F	R^2	F	R^2	F	R^2	F	R^2	F
1	$H = a + bD + cD^2$	0.81	299	0.77	195	0.92	283	0.80	302	0.78	214	0.73	219
2	$H = 130 + bD + cD^2$	0.97	374	0.96	238	0.97	337	0.96	343	0.96	227	0.97	272
3	$H = a + bD^{-1} + c D^{-2}$	0.77	324	0.79	189	0.72	542	0.62	419	0.77	226	0.70	230
4	$H = 130 + bD^{-1} + c D^{-2}$	0.49	1435	0.44	904	0.17	1831	0.24	1566	0.66	708	0.76	813
5	$H = a + b\mathit{Log}D$	0.81	294	0.80	181	0.87	370	0.80	303	0.78	214	0.72	221
6	$H = 130 + b\mathit{Log}D$	0.97	339	0.98	191	0.94	491	0.97	328	0.96	248	0.98	229
7	$\mathit{Log}H = a + b\mathit{Log}D^{-1}$	0.79	334	0.83	189	0.68	548	0.71	456	0.76	232	0.62	244
8	$\mathit{Log}(H - 130) = a + bD^{-1}$	0.82	374	0.85	208	0.69	586	0.83	455	0.77	241	0.70	266
9	$\mathit{Log}H = a + b\mathit{Log}D$	0.86	273	0.83	188	0.94	235	0.88	292	0.81	195	0.71	232
10	$\mathit{Log}(H - 130) = a + b\mathit{Log}D$	0.86	373	0.82	228	0.94	259	0.84	431	0.80	225	0.71	264
11	$\mathit{Log}(H-130) = a + b\mathit{Log}D + c(\mathit{Log}D)^2$	0.90	257	0.87	193	0.94	231	0.92	311	0.82	216	0.73	254

it reflects reality, because height growth is unlikely to be over-estimated for large diameters. Equation 5 frequently produces a good fit in terms of the Furnival Index and the distribution of residuals. However, it produces negative values for height at low diameters. This alone limits its usefulness for the purposes of height prediction in a growth model, where reliable estimates for height are required for all values of diameter. In contrast to this, equation 6 (Figure 2.2 for sycamore) produces positive estimates for height at all diameters, although analysis of the residuals reveals a tendency for over-estimation of height at smaller diameters and an under-estimation at larger diameters. The statistical measures of fit for equation 6 are consistently good with very high values for R^2 and low values for the Furnival index across all species (Table 2.4). The regression curve for this equation is most satisfactory for sycamore where these tendencies in the pattern of residuals are much less pronounced.

Equations 7 and 8 of Table 2.1 possess both an asymptote and an inflection. Equation 7 passes through the origin and equation 8 through the origin for diameter at breast height. Equation 7 always produces a slightly lower Furnival index than equation 8, but R^2 values are often low. The patterns of residuals are frequently unsatisfactory indicating that trends in the data remain unexplained by the equations.

Equations 9 and 10 are logarithmic forms of the power curve; $H = aD^b$, and do not reach an asymptotic value for height. They give a consistently low Furnival index across species, equation 9 always showing a slightly lower value for this index. The pattern of residuals across all species is often satisfactory for both equations, but height is likely to be overestimated in *any* extrapolation to diameters greater than those considered in the regression data. Equation 10 is shown in Figure 2.1 for oak 'standards' and oak 'high forest' and Figure 2.2 for ash.

Equation 11 (Figure 2.1 for oak 'standards' and 'high forest', and Figure 2.2 for beech, birch, sycamore and ash) is not asymptotic and differentiation shows a maximum diameter at $10^{-b/2c}$ when c is negative. However, unlike Equations 1 and 2, this maximum seldom occurs within the range of possible diameters (Table 2.3). Maximum height is attained at diameters of 179 cm for birch, 143.5 cm for sycamore and 139.5 cm for ash. The regression curve for beech has a positive 'c' coefficient and therefore no maximum value at this point. The equation representing

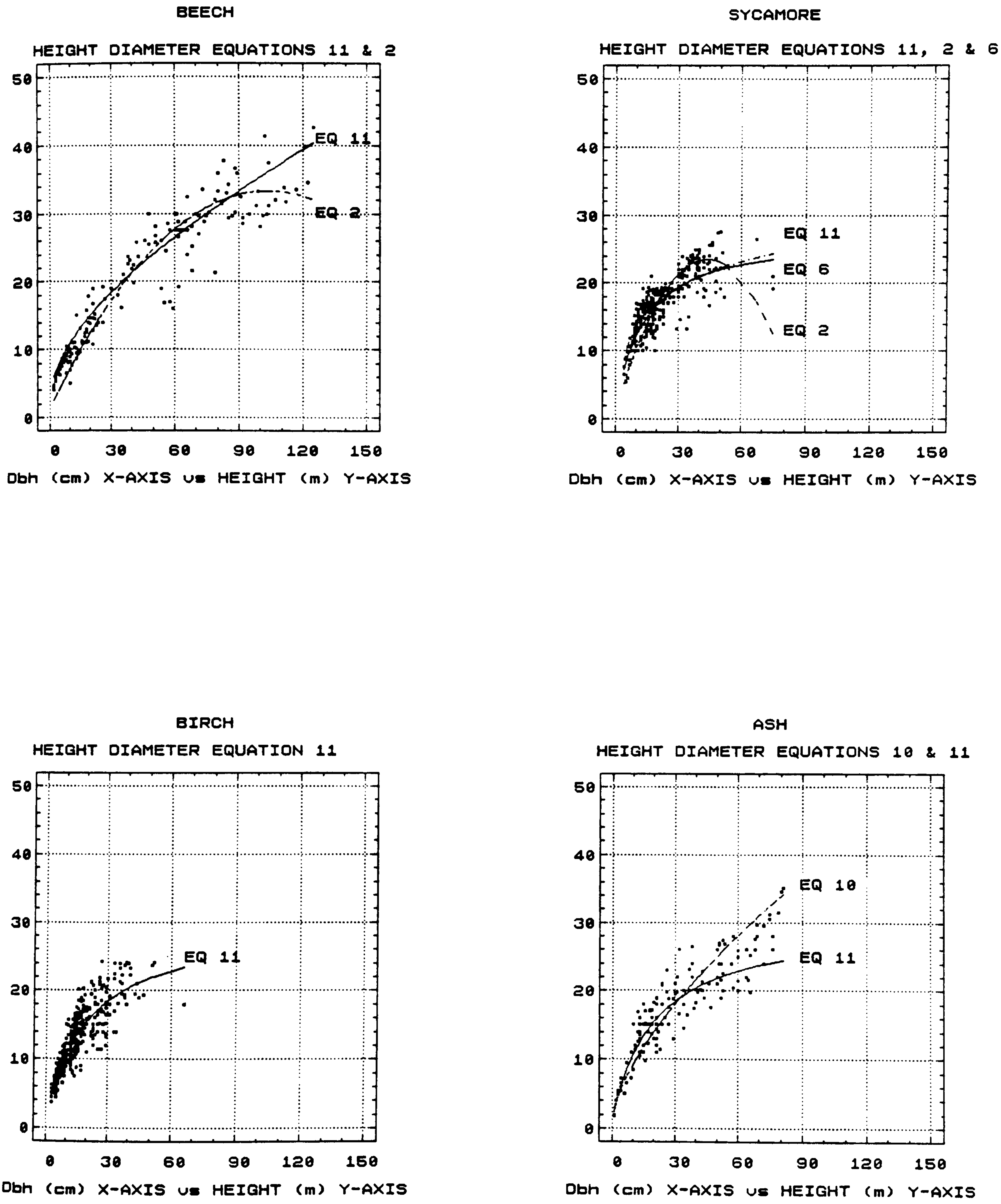


Figure 2.2. Scatterplots of height-diameter data for beech, sycamore, ash and birch (*B. pendula* and *B. pubescens* combined). Fitted curves 2, 6, 10, and 11 are shown. The same scales are used to aid comparison.

oak grown in closer spaced 'high forest' conditions shows a maximum height at 191 cm diameter, whilst the curve for wider spaced 'standards' reaches its maximum at 88.5 cm diameter. Therefore, unlike the parabolic equations 1 and 2, the property of reaching a maximum value does not generally affect the suitability of equation 11. The exception to this is the oak 'standards' data, this curve can *only* be used for the prediction of height up to the diameter at which maximum height occurs (88.5 cm), it is therefore recommended that a curve that does not reach a maximum, within the normal range for diameter, (equation 10) is applied.

Table 2.5. Full regression equations with their residual standard errors for 'high forest' oak, 'standards' oak, beech, ash, birch and sycamore.

No	Full Regression Equations.	S.E.
'high forest' oak		
11	$\mathit{Log}(H\text{-}130)= 2.0249\ 1.274\mathit{Log}D - 0.2792(\mathit{Log}D)^2$	0.059
10	$\mathit{Log}(H\text{-}130) = 2.4897 + 0.5287\mathit{Log}D$	0.071
oak 'standards'		
10	$\mathit{Log}(H\text{-}130) = 2.3445 + 0.4785\mathit{Log}D$	0.083
11 *	$\mathit{Log}(H\text{-}130)= 1.81 + 1.40\mathit{Log}D - 0.35956(\mathit{Log}D)^2$	0.070
beech		
11	$\mathit{Log}(H\text{-}130)= 2.558 + 0.37\mathit{Log}D - 0.05867(\mathit{Log}D)^2$	0.065
10	$\mathit{Log}(H\text{-}130) = 2.345 + 0.582\mathit{Log}D$	0.072
ash		
11	$\mathit{Log}(H\text{-}130)= 1.865 + 1.436\mathit{Log}D - 0.33475(\mathit{Log}D)^2$	0.084
10	$\mathit{Log}(H\text{-}130) = 2.220 + 0.67899\mathit{Log}D$	0.116
birch		
11	$\mathit{Log}(H\text{-}130)= 2.026 + 1.215\mathit{Log}D - 0.26976(\mathit{Log}D)^2$	0.081
sycamore		
6	$H = 130 + 1229.74\mathit{Log}D$	228.83
11	$\mathit{Log}(H\text{-}130)= 2.219787 + 1.0774\mathit{Log}D - 0.2497(\mathit{Log}D)^2$	0.066

* This equation is suitable only for diameters ≤ 88 cm.

2.7.6 Application of height-diameter functions.

The regression analyses show that a variety of equations can be used adequately to describe height-diameter relationships if the constraint of requiring good predictions of height for very small diameters is removed. If this restriction is applied then the number of suitable curves is limited.

The application of height-diameter equations to individual tree growth models requires curves that produce reasonable estimates of height from diameter for all sizes, since competitive interactions are considered for all sizes of tree. The biological principles used in the formulation of such growth models suggest that height-diameter curves should conform to the theoretical condition of possessing a zero diameter at a height of 130 centimetres. This further limits the number of suitable equations. The recommended full regression equations for each species are presented in Table 2.5. Equations 10 or 11 are suitable for 'high forest' oak, oak 'standards', beech and ash, whilst for sycamore both equations 6 and 11 are applicable. Equation 11 should be used for birch.

Furthermore the methodology for the determination of species-specific height-diameter equations used in much of the published literature (Botkin *et al. op. cit*, Aber and Melillo 1982) is not recommended. The overwhelming majority of such growth models use equation 2, with coefficients determined by the physical dimensions of single 'record' trees. This is unsatisfactory for a number of reasons; firstly, data from the U.K. for such trees that have *developed within a forest stand* are largely unavailable, and secondly, equations based on 'record' trees do not include any consideration of the variability of height-diameter relationships in their formulation and, thirdly, use a sample of a single observation to represent an entire species.

2.8 Validity of a single expression for height and diameter.

It is common practice in the U.S. to use one height-diameter relationship for a species on a particular site and under particular management as part of the site class evaluation and construction of yield tables. Utilization of a gap model requires the definition of a single height-diameter relationship for a species, and using data collected from many woodlands provides one method of generating reasonable estimates of height from diameter for a wide variety of sites. If greater precision or site specificity in height estimation for a site is required then similar studies, on a smaller scale could be undertaken.

2.9 Construction of a modified growth equations.

The growth equations that make use of the different height-diameter equations can be constructed in a similar manner to that shown for the original parabolic form (section 2.3.). Thus, if the height-diameter equation number 6 shown in Table 2.5. is substituted into the general form of the growth equation we have;

$$\frac{d(D^2H)}{dt} = G.D^n \left(1 - \frac{D.H}{D_m.H_m} \right)$$

Substituting $H = 130 + bLogD$ as $Hf(D)$

$$\frac{d(D^2.Hf(D))}{dt} = G.D^n \left(\frac{1 - D.(130 + bLogD)}{D_m.H_m} \right)$$

$$\frac{d(D^2.Hf(D))}{dD} = 2D.Hf(D) + D^2.H'f(D)$$

$$H'f(D) = \frac{b}{DLn10}$$

$$\frac{d(D^2.Hf(D))}{dD} = 2D.(130 + bLogD) + \frac{bD^2}{DLn10}$$

$$\frac{dD}{dt} = \frac{G.D^n \left(\frac{1 - D.(130 + bLogD)}{D_m.H_m} \right)}{\frac{(260D + 2DbLogD + bD)}{Ln10}}$$

Therefore;

$$\frac{dD}{dt} \approx \frac{G.D^{n-1}\left(\dfrac{1 - D.(130 + b\mathit{Log}D)}{D_m.H_m}\right)}{(260 + 2b\mathit{Log}D + .4343b)}$$

A similar function can be derived by the substitution of equation 10

$$\frac{d(D^2H)}{dt} = G.D^n\left(1 - \frac{D.H}{D_m.H_m}\right)$$

Substituting $\mathit{Log}(H - 130) = a + b\mathit{Log}D$ as $Hf(D)$

$$\frac{d(D^2.Hf(D))}{dt} = G.D^n\left(1 - \frac{D.Hf(D)}{D_m.H_m}\right)$$

$$\frac{d(D^2.Hf(D))}{dD} = 2D.Hf(D) + D^2.H'f(D)$$

rewriting $\mathit{Log}(H - 130) = a + b\mathit{Log}D$ as;

$$H = 130 + 10^a.D^b$$

and differentiating

$$H'f(D) = 10^a.bD^{b-1}$$

therefore;

$$\frac{d(D^2.Hf(D))}{dD} = 2D.(130 + 10^a.D^b) + 10^abD^{+1}$$

and

$$\frac{dD}{dt} = \frac{G.D^n\left(\dfrac{1 - D.(130 + 10^a.D^b)}{D_m.H_m}\right)}{260D + 10^a.D^{b+1}(2 + b)}$$

$$\frac{dD}{dt} = \frac{G.D^{n-1}\left(\dfrac{1 - D.(130 + 10^a.D^b)}{D_m.H_m}\right)}{260 + 10^a.D^b(2 + b)}$$

A growth equation can be derived from a similar method by the use of equation 11. Full working is shown due to the more complex nature of this equation.

$$\frac{d(D^2H)}{dt} = G.D^n \left(1 - \frac{D.H}{D_m.H_m} \right)$$

Substituting $Log(H - 130) = a + bLogD + c(LogD)^2$ as $Hf(D)$

$$\frac{d(D^2.Hf(D))}{dt} = G.D^n \left(1 - \frac{D.Hf(D)}{D_m.H_m} \right)$$

re-writing

$$Log(H - 130) = a + bLogD + c(LogD)^2$$

as

$$H = 130 + 10^a.10^{(bLogD)}.10^{c(LogD.LogD)}$$

$$= 130 + 10^a.D^{(b+cLogD)}$$

and writing; $H = 130 + 10^a.D^{(b+cLogD)}$ as $Hf(D)$

$$\frac{d(D^2.Hf(D))}{dD} = 2D.Hf(D) + D^2.H'f(D)$$

generally;

$$\frac{d(a^{f(x)}}{dD} = d\ (e^{f(x).Lnx})$$

$$\equiv Lnx.f'(x).a^{f(x)}$$

consequently;

$$H'f(D) = \frac{Ln10(b+cLogD).(130 + 10^a.D^{(b+cLogD)})}{DLn10}$$

and

$$\frac{d(D^2.Hf(D))}{dD} = 260D + 2.10^a.D^{b+1+cLogD}+(b + cLogD).(10^a.D^{b+1+cLogD})$$

$$= 260D + 10^a.D^{(b+1+cLogD)}.(2 + b + cLogD)$$

Finally, the resulting growth function can be expressed;

$$\frac{dD}{dt} = \frac{G.D^{n-1}\left(1 - \dfrac{D.(Hf(D))}{D_m.H_m}\right)}{(260 + 10^a.D^{(b+cLogD)}).(2 + b + cLogD)}$$

Where; n represents the exponent of the diameter to leaf weight relationship, D is the tree diameter and all other parameters are species specific derived from regression analysis as previously described.

CHAPTER 3. Increment patterns and modified growth equations.

This chapter describes investigations into growth trends in the broadleaved species oak, ash, beech, birch, and sycamore. The purpose is to use field data that represents the growth trends of the species in order to calibrate the growth equations developed in Chapter 2. Reliable estimates of individual tree growth may then be derived from the use of the resulting growth equations.

For the purpose of clarity, all reference to 'growth functions' or 'growth equations' should be taken to mean growth equations used in published gap-models (section 2.3), or the modified versions developed in Chapter 2.

3.1 The growth constant 'G'.

The purpose of the growth constant 'G' is to establish the maximum rate of growth for an individual tree, in optimum growing conditions, through its influence on the values produced by the growth function. Noble (1988 *pers. comm.*) states that the 'G' parameter is one of the most sensitive in gap-models that use this growth function. If this is the case, then good estimates are a prerequisite for the meaningful prediction of relative growth rates of tree species.

The growth rate constant 'G' used in gap-models has repeatedly been determined arbitrarily. The basis for the values used was the crude observation that a tree reaches 2/3 of its maximum size at 1/2 its maximum age. Botkin *et al.* (1972), Aber and Melillo (1978), Shugart and West (1977), Mielke (1978), Tharp *et al.* (1978), Shugart *et al.* (1981) all make this assumption. Only Doyle (1981) refers to individual tree growth data for the scaling of growth, in a model for tropical moist forest in Puerto Rico.

Thus, the growth rate constant is based on estimates of the maximum age of species and on the dimensions of one single 'record' tree that is assumed to be representative of its species. Estimation of the 'G' parameter in this manner is not possible (or desirable) in the U.K. since few, if any, trees have been reported of record size and age that have grown in a closed forest environment. In addition some species do not conform to the pattern of growth assumed by Botkin *et al.* (*op. cit.*). They realised this weakness and noted that such estimation was "particularly inaccurate for very short-lived species and long-lived shade tolerant species such as beech (*Fagus grandifolia*)" and also that "Probably a much better way of determining a value of 'G' for a species lies in demanding that the maximum possible annual diameter increment given by the growth equation be equal to some value dD_{max} which could be determined from field observations".

3.2 Calibration of growth rates: stand versus individual tree data.

Shugart (1984) made use of stand growth data, by matching 'mean tree' diameter-age curves from stand growth against different values for 'G' and selecting the value that gives the best visual fit to the plotted data. However, since the growth equation represents the *maximum* growth rate for a species, calibration from 'mean tree' dimensions collected from stands is theoretically inappropriate unless tree spacings are assumed to be of sufficient magnitude to ignore any growth reduction due competitive interactions.

Certainly, increment data collected from stands and expressed per unit area are not suitable for use in the calibration of the growth rate parameter 'G' which applies to individual trees. It is not possible to match predictions from growth equations of annual increment and basal area curves for individual trees to curves for stands of trees. The shape of the curves should be similar but the timing of individual tree maximum basal area increment occurs much later than that for the stand as a whole. Assmann (1970) states; "The decline of the [stand] mean annual increment is particularly noteworthy because it begins at a considerably earlier age than in the individual trees which constitute the stand". The reason for this difference is linked to the decrease in the number of individuals and the resultant increase in the growing space available to each tree. Mean annual increment (MAI) is conventionally expressed in terms of average volume production per unit area per year, whilst the consideration of the mean annual increment of an individual tree does not include the relationship to area. In addition, individual tree basal area increment always reaches a maximum considerably later than diameter increment. Even when the rate of diameter increment is decreasing, a narrow annual ring added to a large diameter often gives a large basal area increment (Figure 3.1).

Ideally, maximum growth rates should take account of maximum volume increment, which occurs very late in the growth of an individual. However this is difficult to establish by direct measurement for an acceptable sample of trees over time. Estimates of 'G' for each species should, therefore, be matched to diameter and basal area increment data, not produced from an arbitrary assumption.

3.3 Method for the calibration of growth rates.

The method of calibration of the growth rate parameter 'G' was based on increment cores taken from widely-spaced trees on fertile sites. The justification for this is based on theoretical and practical criteria. The assumption regarding selection of widely-spaced individuals is that the intensity of competitive interactions is low in comparison to trees developing in a stand, and as such, will more likely represent the maximum growth rate possible for the species. Assmann (*op. cit.*) commented; "The available growing space has an important influence on the diameter and basal area increment of individual trees", "basal area increment also increases with increasing growing space until the maximum utilisable space is reached." This implies that maximum rates of diameter and basal area increment should be assessed from widely-spaced trees, because the space available is not likely to limit growth. The selection of fertile sites for each species assists in the estimation of *maximum* growth rates. Dendrochronological techniques use trees growing on marginal sites because normal tree growth patterns are small in comparison to the effect of climatic variation (Fritts 1976). It is reasonable to assert that the converse is also true, trees growing on fertile sites with a minimum of competitive interaction will show a stronger growth pattern, and the effects of climatic variation will be shown to a lesser degree.

The value of the parameter 'G' was determined for each species by fitting curves to field measurements taken from individual trees. Sample trees were selected on the basis of their position (proximity to other trees), the soil quality (usually good agricultural land), and the form of the crown. Large trees were selected, but those with a great depth of crown and characteristics of open-grown form were avoided, in preference to trees displaying characteristics more often associated with 'high forest' trees. The selection of trees in this manner represented

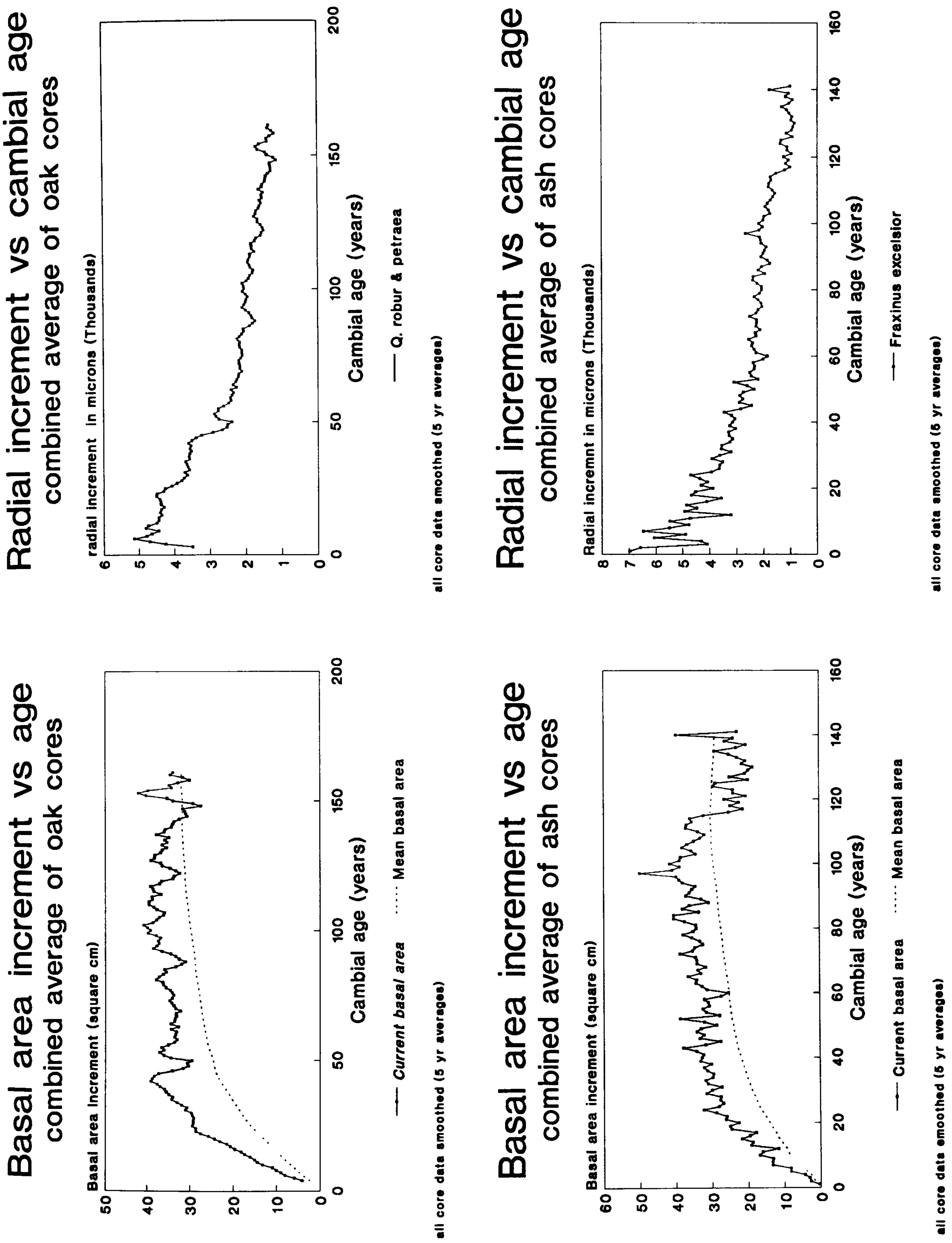


Figure 3.1. Basal area increment and radial increment curves versus cambial age at breast height, for core data from ash and oak (*Q. robur* and *Q. petraea* combined).

an attempt to avoid sampling of diameter increment at breast height in trees that are known to allocate biomass to the base of the trunk at a different rate to trees grown in 'high forest' conditions (Assmann *op. cit.*, Jobling and Pearce 1977).

Cores were taken at breast height with a 5mm Pressler borer, allowed to dry, polished on a fine grade belt sander, mounted on plywood blocks, and then analysed under the microscope with an electronic incremental digitiser linked to a sliding stand. This gave measurements accurate to the nearest 2 micrometres. Readings were taken of ring widths from the pith outwards with ring measurements from off-centre cores being corrected following the method of Liu (1986). Since large trees were selected from areas where past management and stocking were unknown, any evidence of suppression of growth shown by the ring increment pattern resulted in rejection from the analyses. The number of cores used in the study were; ash 13, oak (*Q. robur* and *Q. petraea* combined) 22, beech 8, sycamore 10, and birch (*B. pendula* and *B. pubescens* combined) 10.

Recorded values of diameter increments for individuals of a species were smoothed to minimise the effects of annual climatic variations on ring widths by the use of running five year averages. The smoothed data for each individual were used to produce average diameter, and basal area increment curves for each species. Where cores failed to reach the pith an estimate of the number of rings missing was used in order to match rings of the same cambial age for the generation of the mean curves. The mean curves were later used in the initial matching of growth curves to increment core data. Predicted annual basal area and diameter increment curves from the growth equations derived for each species were matched empirically, as closely as possible to this *individual* tree growth data taken from field measurements. However, the raw increment data from cores were later used in the nonlinear regression analysis (section 3.3.2).

3.3.1 Patterns of growth from core data.

Maximum diameter increment occurs very early and then decreases (Figure 3.1). This is a common feature of increment data and Fritts (*op. cit.*), Eckstein (1972), Fletcher (1986), and Warren (1980) all use a negative exponential to approximate this trend and correct ring width data for dendrochronological analysis. The pattern conforms well with the ring increment data from the sample cores (Figure 3.1). Plots of basal area increment against cambial age (at breast height) for oak and ash show trends that are typical for all the species considered. It can be seen that the maximum basal area increment occurs, as expected, much later than maximum diameter increment represented in the plots of radial increment versus cambial age. The maximum mean basal area increment for *individual* oak trees occurs at approximately 150 years, whilst figures for Yield Class 8 stands of oak taken from Forestry Commission management tables (Hamilton and Christie 1971) show the corresponding maximum to be at approximately 30 years. Similarly for ash the maximum mean basal area increment for individual trees is at about 120 years and the equivalent timing for Yield Class 10 ash, from tables, is approximately 25 years. This confirms the validity of using individual tree increment data discussed in section 3.2.

3.3.1 The effect of 'G' on the growth function.

Curves for basal area increment derived from the new growth equations (Chapter 2) were produced for each species. Empirical visual matching of the growth function to curves derived from the core sample data was attempted. The intention in the first instance, was to match the growth curve to the field data by alteration of the parameter 'G' alone. This was attempted for each species. The results of alteration of 'G' are shown in Figure 3.2. for ash, but they are typical of the behaviour of the function for all the other species considered, including the oak 'standards'. The value of leaf area exponent used in the initial attempts at calibration was 2 (Figure 3.2). This is the value assumed in published gap-model growth equations (section 3.3.3).

Reducing the value of 'G' decreases the magnitude of the maximum basal area increment and lengthens the cambial age (at breast height) at which this maximum occurs. Conversely increasing 'G' has the opposite effect of amplifying maximum basal area increment and reducing the corresponding cambial age of the maximum.

It is evident from Figure 3.2 that it is not possible to achieve a good match between observed growth data and projected growth from the equation by manipulation of 'G' alone. It is possible to match the magnitude of basal area increment, but the corresponding timing will be unsatisfactory. Alternatively, if the timing of the maximum basal area is matched then its magnitude is too great.

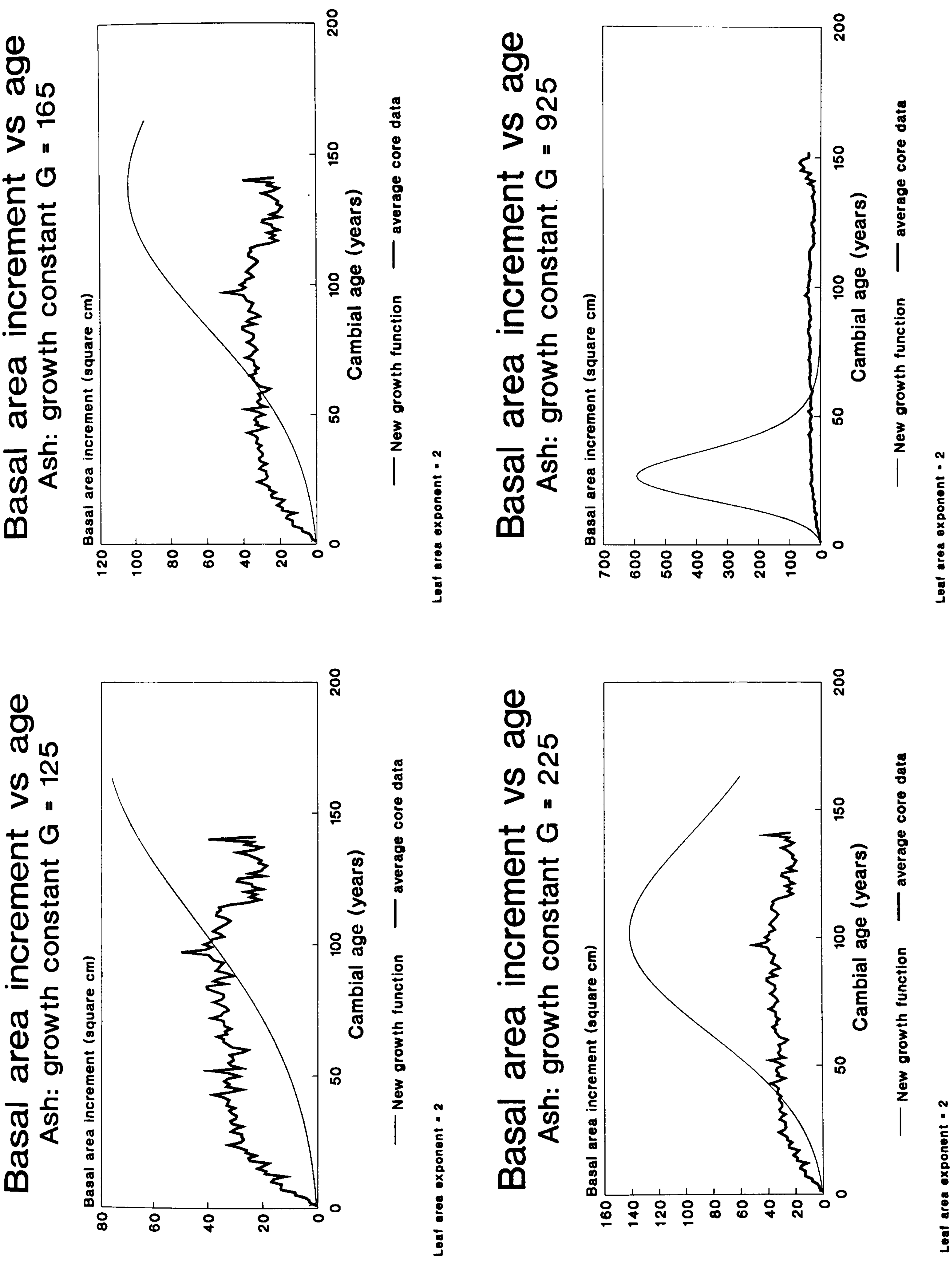


Figure 3.2. Basal area increment curves for ash from core data and predicted values from the new growth equation. Each plot represents an attempt to obtain a good visual fit by variation of the 'G' parameter alone. A leaf area exponent of two (assumed in published literature) was used.

3.3.3 The exponent of the diameter-leaf weight relationship.

It has already been noted in section 1.8.3 that a fundamental premise within the growth function is the biological relationship between growth and leaf area. This is included in the function by relating leaf area to diameter. The form of this relationship being;

$$\text{Leaf weight} = C_i.D^n$$

Leaf weight is assumed to be proportional to leaf area. C_i is a species specific constant and D is the diameter of the tree.

Botkin *et al.* (1972) used this relationship and stated; "The exponent used in the leaf weight to stem diameter relationship [n] has the effect of steepening the [growth] curve for intermediate aged trees. The exponent could be as small as one or as large as three without drastically altering the overall shape of the final growth curve.", Sollins *et al.* (1973) use an exponent of 2.939, whilst a value of 2 is assumed in the original published versions of the growth equation.

No attempt has been made to establish this relationship from field measurement. It has instead been used as a means of empirically adjusting the form of the growth curves to conform with the patterns evident from the analysis of the increment core data.

The exponent used for the relationship between diameter and leaf weight affects the timing and the magnitude of the diameter and basal area increment curves. Increasing the value of the exponent greatly increases the maximum value for diameter increment and reduces the time taken to reach maximum basal area increment. Since there is no biological rationale for limiting the exponent to a constant value for all species, curves were fitted to field data by alteration of the 'G' parameter in conjunction with the exponent of the diameter-leaf area relationship. A range of values w~~ere~~as tested and the most satisfactory results were produced with values for the leaf area exponent between 0.9 and 1.5. The resulting growth curves produced a good visual fit to the measured data.

3.4 Parameter estimation of G and the leaf area exponent from non-linear regression.

Since the growth equation cannot be made linear by transformation (intrinsically non-linear), an iterative non-linear regression procedure is required for parameter estimation. The results from non-linear regression can be influenced by the starting parameters and, unlike linear regression, may not necessarily provide a unique best, unbiased, solution for a given set of variables Payandeh (1983). Therefore empirical estimates for 'G' and the leaf area exponent (from visual fitting) were used as the starting parameters in nonlinear regressions of diameter versus diameter increment using the increment core data. These variables were used since diameter is the basis for the prediction of diameter increment in the growth equation. All of the analyses were performed by the non-linear regression computer program included in STATGRAPHICS version 2.6 which makes use of Marquardt's compromise: a compromise between using a straight linearisation method and the method of steepest descent. It appears to combine the best features of both while avoiding their most serious limitations and is discussed by Draper and Smith (1966). Table 3.1. shows the detail of the estimate for each species. Figures 3.3 and 3.4a. show the raw core increment data and the curves of best fit.

Table 3.1. Results produced from non-linear regression analysis of growth curves and increment core data. 'HF' = high forest oak, 'S' = oak standards.

Species	Parameter	Standard error	Source	Sum of squares	DF	Mean Square	F ratio
Oak 'HF'	G = 1573.54	101.542	Regression	263.69	2	131.85	1931.36
	n = 1.30356	0.019151	Residual	47.04	689	0.0682	
Oak 'S'	G = 824.167	53.4127	Regression	268.71	2	134.36	2202.73
	n = 1.29187	0.01898	Residual	42.03	689	0.0610	
Ash	G = 2622.00	227.709	Regression	351.08	2	175.54	2621.17
	n = 1.15321	0.02489	Residual	76.61	1144	0.0670	
Beech	G = 1342.000	225.589	Regression	65.586	2	32.793	569.24
	n = 0.9100	0.0509	Residual	31.742	551	0.0576	
Birch	G = 2977.578	199.795	Regression	579.76	2	289.87	1816.007
	n = 1.33906	0.02450	Residual	54.591	342	0.1596	
Sycamore	G = 2916.957	399.136	Regression	165.27	2	82.637	968.877
	n = 1.20746	0.04147	Residual	18.081	212	0.08529	

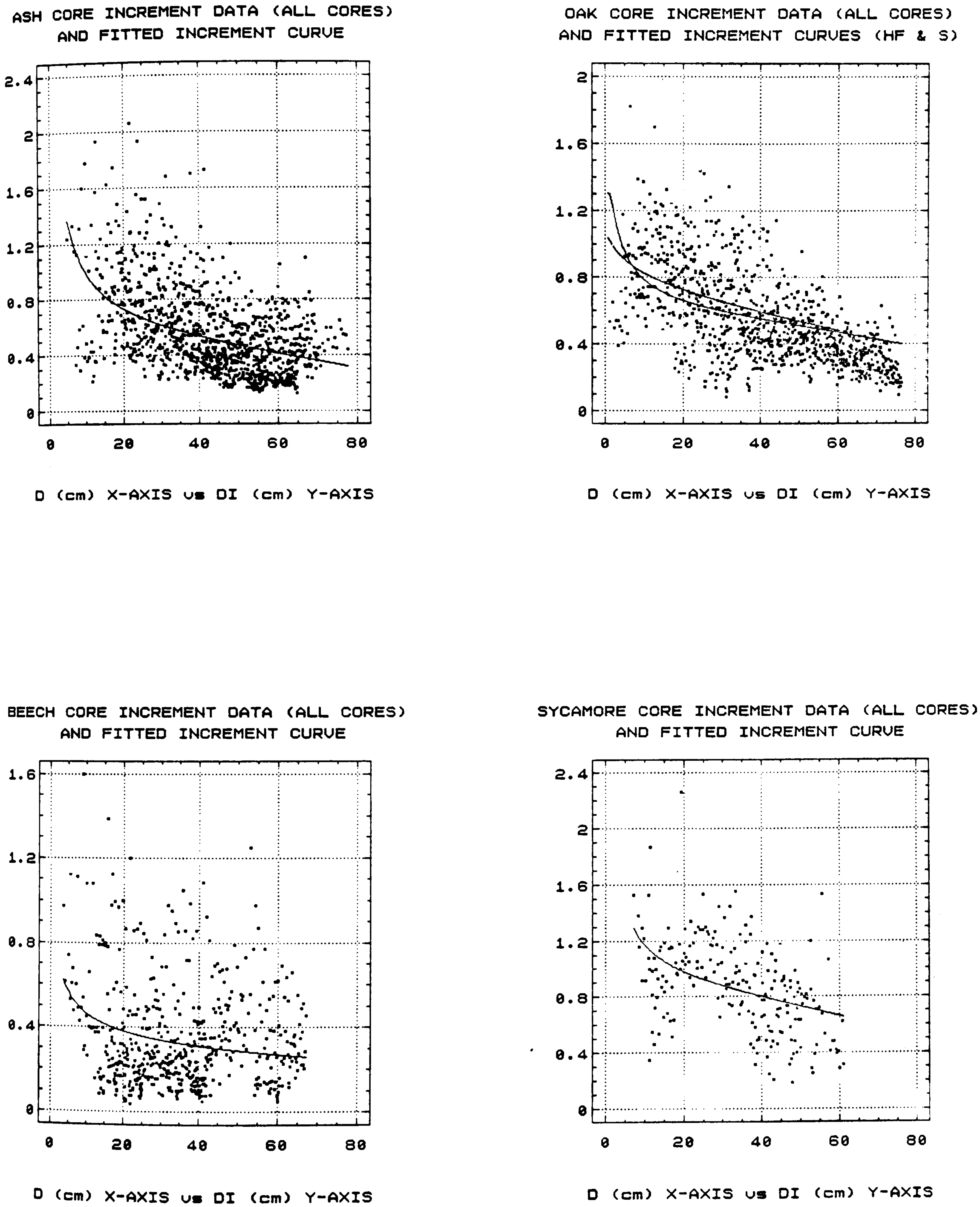


Figure 3.3. Diameter increment curves from the new growth equations, fitted by nonlinear regression software to the raw core data, for ash, oak ('high forest' and 'standards'), beech and sycamore.

3.5 Recommended species specific growth equations

The growth equation resulting from the substitution of height-diameter equation 11 (sections 2.7.3-2.9) is suitable for oak ('high forest'), ash, beech, birch, and sycamore. Oak 'standards' require a different growth function resulting from the substitution of equation 10. The values for parameters from nonlinear regression and the coefficients resulting from the height diameter studies (sections 2.7.3-2.9) are presented in Table 3.2. The growth function resulting from the substitution of equation 11 is;

$$\frac{dD}{dt} = \frac{G.D^{n-1}\left(1 - \dfrac{D.(Hf(D))}{D_m.H_m}\right)}{(260 + 10^a.D^{(b+c\mathit{Log}D)}).(2 + b + c\mathit{Log}D)}$$

Table 3.2. parameters and coefficients for the growth equation used for oak ('high forest') ash, beech, birch, and sycamore.

	Species	G	n	a	b	c	$D_{max} \times H_{max}$
	oak ('high forest')	1574	1.3	2.025	1.274	-0.2792	598751
	ash	2622	1.15	1.865	1.436	-0.3348	355000
	beech	1342	0.91	2.558	0.37	-0.0586	532500
	birch	2978	1.339	2.026	1.215	-0.2698	132000
	sycamore	2916	1.207	2.220	1.077	-0.2497	364203
*	oak ('standards')	824	1.207	2.345	1.274	-----	390000

* For oak developing in stands of wider spaced 'standards', the growth equation to which the coefficients apply is;

$$\frac{dD}{dt} = \frac{G.D^{n-1}\left(\dfrac{1 - D.(130 + 10^a.D^b)}{D_m.H_m}\right)}{260 + 10^a.D^b(2 + b)}$$

3.6 Comparison of published growth equations and 'new' growth equations.

The methodology for producing the growth equations used in published work (eg Botkin *et al. op. cit.*, Aber and Melillo *op. cit.*), highlighted in sections 2.3. and 3.1, was adopted in order to provide a basis for comparison with the 'new' equations (Chapter 2). There are two possible procedures resulting from the use of the original methodology which require 'record' trees. Firstly, the largest trees taken from field measurements (described in Chapter 2) could be used, to approximate 'record' trees or, secondly, the published 'record' trees Mitchell and Hallett (1985) can be used despite the fact that they are unlikely to represent trees developed in forest conditions. For the sake of completeness the results using of these two interpretations of the published methodology, as applied to U.K. conditions, will be compared to the new growth equations.

Mitchell and Hallett (*op. cit.*) produce two estimates for a species, one for the tallest tree, and the other for that of greatest diameter. Data from the tallest trees are adopted for use in the comparative studies since these measurements are likely to represent trees that have form of greater similarity to that expected of high forest development, than data from the trees of greatest diameter.

3.6.1 The original method of deriving growth functions

In order to calculate the growth constant 'G' using the assumptions in the published methodology, an estimate for the maximum age of each species is required. This, in the absence of any published information, can only be an educated guess based on a knowledge of the biology of a species. Table 3.3. includes estimates of maximum age that were used.

The parameters for the parabolic height-diameter functions are set such that the maximum value produced corresponds with the largest tree measurements from the expressions;

$$b_3 = \frac{(H_{max} - 137)}{D^2_{max}} \qquad b_2 = \frac{2.(H_{max} - 137)}{D_{max}}$$

Table 3.3. The largest trees recorded in the studies of height-diameter relationships, and the 'record' trees taken from Mitchell and Hallett (*op. cit.*) showing diameter at breast height (dbh) in centimetres and total height in metres.

Species	Published 'record' trees		Field-measured trees		Maximum age (years)
	dbh	height	dbh	height	
Quercus robur	118	42	130	33 *	300
Quercus petraea	148	43	--	--	300
Fraxinus excelsior	48	41	81	35	200
Betula pendula	75	28	52	24 •	90
Betula pubescens	61	27	--	--	90
Fagus sylvatica	171	44	125	43	300
Acer pseudoplatanus	115	40	67	23	120

* measurement from a combined data set for both species of oak, • measurement from a combined data set for both species of birch.

The parabolic height-diameter equation ($H = 137 + b_2D + b_3D^2$) is then substituted into the original growth function (shown in section 2.3) and the value of the growth rate constant is determined. Botkin *et al. (op. cit.)* solve the growth equation in terms of 'G' from the assumption of a tree reaching 2/3 its maximum size at half of the maximum age, they also produce the approximation;

$$DI_m \approx 0.2\,G.D_m/H_m$$

where DI_m = maximum diameter increment for the species, set at 0.7 cm/year for beech (*Fagus grandifolia*) and 1.0 cm/year for all other species. This can be rearranged to provide an estimate of 'G';

$$G \approx 5DI_m\,H_m/D_m$$

For the purpose of the comparison beech (*Fagus sylvatica*) was assigned a maximum diameter increment (DI) of 0.7 cm/year and all other species were assigned a maximum value of 1.0 cm/year for 'G'.

Table 3.4. Parameters for the use in the original form of the growth equation, the data column refers to the source of the species measurements, P = published data (Mitchell and Hallett *op. cit.*) and F = data from fieldwork.

Species	Data	G	b_2	b_3
Quercus robur	P	177.97	68.86	0.2918
Quercus petraea	P	145.27	56.26	0.1900
Fraxinus excelsior	P	427.08	165.13	1.7200
Betula pendula	P	186.67	71.01	0.4734
Betula pubescens	P	221.31	84.03	0.6888
Fagus sylvatica	P	90.06	49.86	0.1458
Acer pseudoplatanus	P	173.91	67.18	0.2921
Quercus combined	F	126.92	48.66	0.1872
Fraxinus excelsior	F	216.05	83.04	0.5126
Betula combined	F	230.77	66.61	0.2664
Fagus sylvatica	F	120.40	87.04	0.8369
Acer pseudoplatanus	F	171.64	64.57	0.4818

The growth function parameters for the original equation are presented in Table 3.4, where they correspond to the growth equation;

$$\frac{dD}{dt} = \frac{G.D\left(1 - \dfrac{D.H}{D_m.H_m}\right)}{274 + 3b_2D - 4b_3D^2}$$

The growth functions produced by using the different methodologies are presented in Figure 3.4b for birch and 3.5. for , oak, ash, beech and sycamore. 'Published methods' 1 and 2 refer to the functions derived from the Mitchell and Hallett and the field measurement data respectively. It can be seen, without recourse to rigorous statistical tests, that the published methodologies, based on either data produce very different results to the new approach. As a means of comparison Figure 3.5 for ash shows the average core data.The association of the new method growth curve with the core data is similar for all the species considered. The new equations produce estimated growth patterns that correspond well with those measured from the field data. The equations produced from the alternative interpretations of the published methodology, do not.

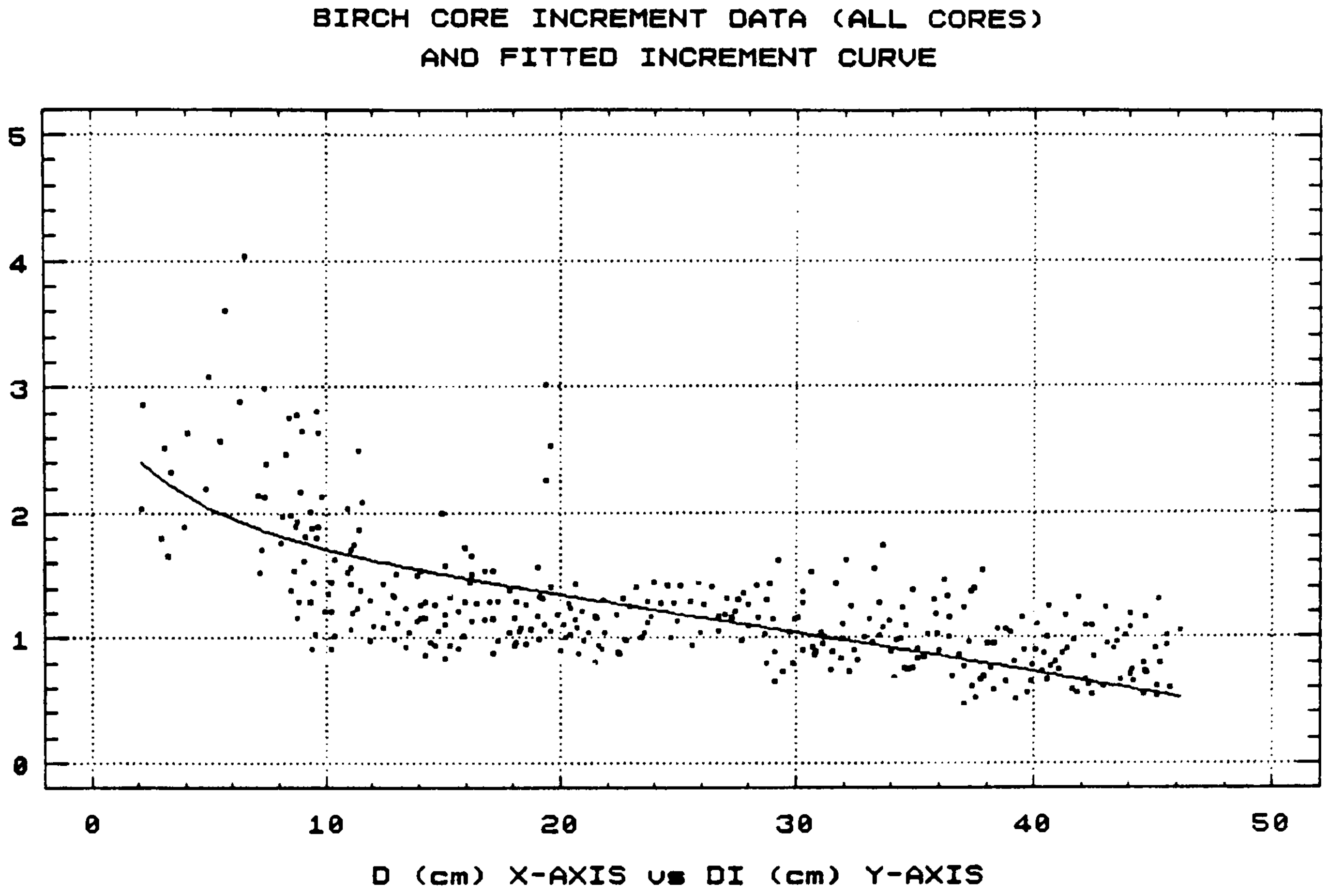


Figure 3.4a. Diameter increment curves from the new growth equation, fitted by nonlinear regression software to the raw core data, for birch (*B. pendula* and *B. pubescens* combined).

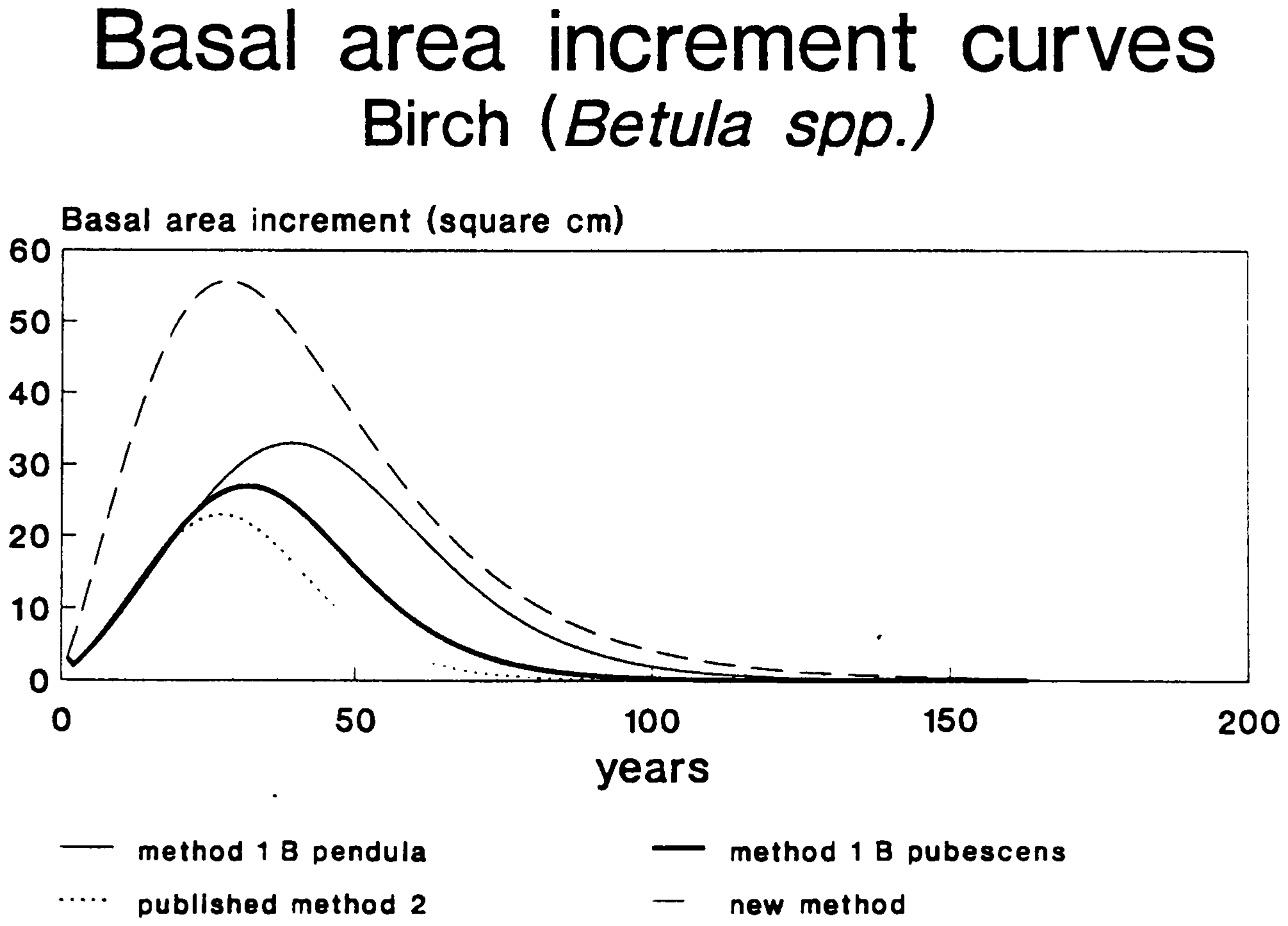


Figure 3.4b. Basal area increment curves for birch produced by three versions of the published methodology, and that produced by fitting to observed data.

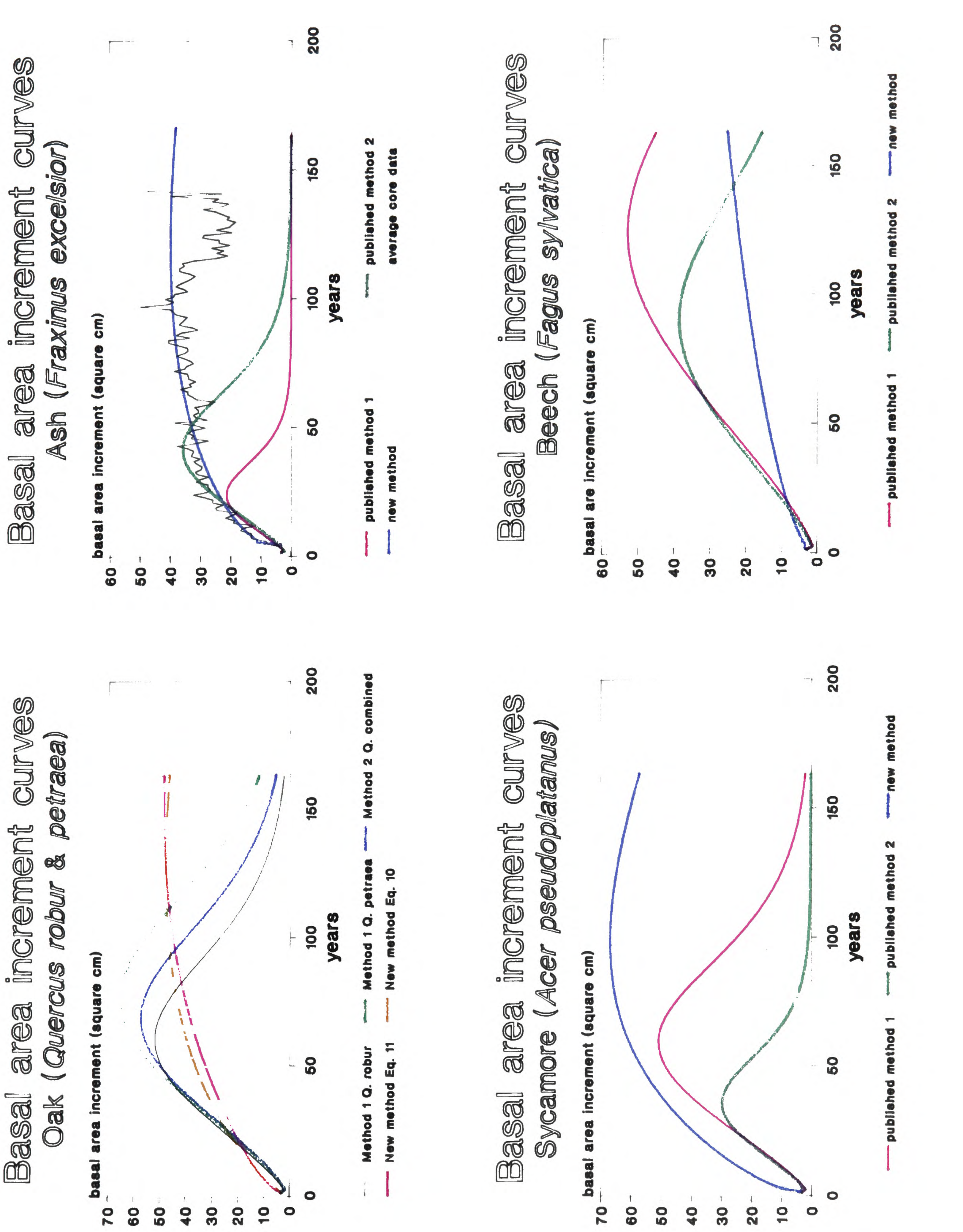


Figure 3.5. Basal area increment curves for oak, ash, beech and sycamore produced by versions of the published methodology, and that produced by fitting new growth equations to observed increment data. The mean basal area increment curve from core data is shown for ash.

3.7 Summary of growth calibration studies.

It is therefore concluded that the simplest yet most reliable method of calibrating growth curves for broadleaved species in the U.K. is by the use of diameter increment data collected from widely-spaced trees tending towards high forest form. The equations produced in Chapter 2 provide reliable estimates for diameter increment, when calibrated against increment data from field measurements. It is also clear that the resulting growth functions should be substituted for the existing growth equations in gap-models that aim to describe the biomass dynamics of broadleaved woodlands in the U.K. For species that have not been dealt with in this study, this method of calibration should be used to derive similarly suitable growth equations.

CHAPTER 4. Alteration of existing Gap-models for U.K. conditions.

This Chapter covers work aimed towards the incorporation of modified growth equations into their intended context, namely within gap-models for mixed age polyspecific broadleaved woodland development. The Chapter begins by summarising the adaptations made to the selected original published versions of the models, and proceeds towards an appraisal of the effect on the output of such models of installing the modified growth equations. The effect of further modifications with the aim of improving the models is also investigated and discussed. Finally the results generated from the model are compared to data available from field measurements.

4.1 General principles for the modification of models.

It is tempting to include new, independently tested, relationships into existing models, and automatically assume that the results are immediately superior to those previously produced. This may not be justified and a critical appraisal of any alteration should be adopted (see Foreword, parts *v* and *vi* of the systems analysis framework). Indeed, the results may not be realistic both before and after a modification has been completed. A formal method of assessment must, therefore, be implemented as part of the systems analysis framework. This assessment should involve detailed validation and simple verification (section 4.2).

The most important aim for improving gap-models of forest development is, to *attain a realistic modelled interaction between the fundamental ecological processes of regeneration, growth and mortality*. If this is achieved then models of this type may be applied to the management of mixed broadleaved woodlands and the response of such models to simulated management interventions will be more likely to reflect reality.

4.2 Validation and verification in testing models.

The fundamental premise regarding validation of growth models is most aptly given by Vanclay (1990) where he states; "Validation is something of a misnomer. An hypothesis or model can never be proved correct; it can only be proved incorrect. However, the failure of a number of attempts to prove an hypothesis wrong gives more credence to the hypothesis." This should be the role of validation in growth modelling. Reynolds *et al.* (1981) reduce the process of validation to three main stages. The first is to ensure that the individual functions that make up the model are sound, for example the growth functions developed in Chapters 2 and 3. The second involves checking the syntax of the model, and that its behaviour corresponds with that expected or intended. The final stage is to compare the output of the model with the observed behaviour of the forest under a variety of conditions. Verification involves detailed checking of the output of a model, or components of it, to establish that a known 'starting point or value' will produce a known result. The difference between verification and validation is that the process of verification sets out to confirm what is already known and can be reproduced (and checked) by use of the model, whilst validation is a methodology for testing predictions where the output cannot be checked with certainty.

4.2.1 The problem of circularity.

One of the problems inherent in the development of the models by workers at Merlewood was the likelihood of circularity between data collection, verification, and validation. This was largely because all the parameters required to produce and verify the components, and the data to run the models, were collected from Meathop wood, which also provided the recurrent inventory data against which the performance of the models were assessed.

One advantage of the modifications made in this study is that all the parameters regarding tree growth, both in terms of diameter or basal area increment and in height development, were produced independently of the site against which the modifications were tested. Verification and validation are more useful techniques under these circumstances.

For most practical purposes, producing a growth model that behaves in a manner that conforms with known phenomena in a forest ecosystem relies on numerous attempts to verify the output of the model. Where there are differences between model predictions and what is known to occur, the assumptions leading to the disparity may need reassessment and alteration, followed by further attempts at verification. Finally, when the model withstands all attempts at disproving its validity via verification, then rigorous validation techniques should be used (section 4.12).

4.3 Models to be considered for modification

Chapter 1 discusses three gap-models in some detail; JABOWA, FORTNITE and FORET. Of these only FORTNITE and FORET have been developed and adjusted, to some extent, for U.K. conditions. They are the only examples of gap-models for broadleaved species that are in use in this country to date. The intention was to compare output from one or more models to the data available from recurrent inventory sample plots in Meathop Wood (Cumbria), part of an International Biological Programme (IBP) research site. Meathop Wood contains the tree species oak, ash, birch, sycamore and hazel (*Corylus avellana*).

4.4 Existing versions of gap-models for U.K. conditions.

FORET (Shugart and West 1977) and FORTNITE (Aber and Melillo 1982) have been altered from their published forms. Both models have been developed to include data and certain relationships relevant to U.K. conditions. Much of this work has been carried out at the Institute of Terrestrial Ecology at Merlewood, by Harrison and Ineson (1987, 1988) and Sykes (1989).

All versions of both models are written in FORTRAN and have been compiled to run on a VAX 8600 computer. Both can be run for a set number of years for any number of simulations. Since the model can produce stochastic events of mortality and regeneration, previous workers have programed the model to produce results from repeated simulations.

Using a number of simulations of forest development produces results that would represent the average inventory data of recording an equal number of permanent sample plots (measured annually) in a non-uniform mixed age polyspecific woodland.

One alteration common to both models was the substitution of the random number generator for a superior routine available from the NERC subroutine library. This modification alone limits the use of the model to institutions with access to NERC computer facilities. However, this has eliminated problems of inconsistent results, first noticed in FORTNITE.

4.5 Priorities for gap-model development.

The order of priority for development of these models was established by the consideration of three criteria. Firstly, the individual complexity of the model; the simplest should be modified first. The second criterion is to select the model with greatest potential to yield results relevant to management decisions whilst, thirdly, requiring the least amount of data. Using these criteria and taking into account the criticisms already highlighted for FORTNITE, the model FORET was the preferred choice for further development in the first instance.

4.6 FORET, modifications made by previous workers.

Two versions of FORET existed before the modified growth equations were incorporated into the growth subroutine of the model. One version started the growth simulations from a bare plot, ie a plot with no trees present. The alternative version started the simulations with the plot in a state of development, in terms of species and diameter distributions, that corresponded to the conditions in Meathop wood as they were in 1967.

Both versions assume a simulated plot size of 10 m x 10 m, rather than the theoretically more acceptable 1/12 ha used in the original (section 1.7). This was because all data collected from Meathop wood was based on 10 m x 10 m sample plots. The plot size assumed in the model is related to the growth multiplier that is supposed to reflect density dependent effects (section 1.6.3.3). In fact, simulated biomass production is limited as it approaches the pre-defined site maximum. The size of the site is defined in terms of the maximum biomass it can support. This maximum is set to the value found from field measurements of above-ground biomass taken at Meathop and nearby woodlands (Sykes & Barr 1973).

A choice of values for use in the climatic growth multiplier (section 1.6.3.2) was available: either the measurements taken from meteorological data collected at Merlewood and Meathop wood, or the original American value could be used. This value is also used in the regeneration subroutine.

In addition, both versions of FORET use the parabolic height-diameter relationship derived from regression analysis of a very limited number of trees from Meathop wood. The values for the growth rate constant 'G' were set in accordance with the published methodology (examined in section 3.6) and are unlikely to be representative of the actual patterns of growth. Relationships between diameter and biomass were derived from field measurements for each species but, for unknown reasons, were not included in the model. However, there is scope to include similar relationships developed by Corbyn *et al.* (1988), that can predict the partitioning of biomass into branchwood and stem wood.

Output from the model was modified at Merlewood by the inclusion of plotting routines for actual and percentage biomass production over time. A plotting routine for the diameter distributions was also added, this was intended to represent the diameter distribution, by species, for selected years during the simulation. However, this suffered from an error that caused summation of the diameter distribution in any one year for each simulated plot. Thus the diameter frequency for any year became directly proportional to the number of simulations (plots considered) in a predictive run of a model.

Figure 4.1 shows the simulated forest development in terms of biomass from the 'bare plot' version of FORET, modified for U.K. conditions, but not including the new growth equations.

4.7 Initial modifications to FORET for the addition of the new growth equations.

The whole functioning of the model is largely dependent on values produced by the growth subroutine. The inclusion of new growth equations and the assessment of the effect of growth multipliers is an aspect of the model that requires thorough investigation.

All modified syntax is shown (emboldened) in Appendix 2 in the program listing. The modifications were initially restricted to alteration of all parts of the model that make use of height-diameter equations and the core of the biomass increment routine, the growth equation. It was assumed that oak development in Meathop wood would follow that of high forest oak, and therefore only one form of the equation was required. The inclusion of this growth equation and

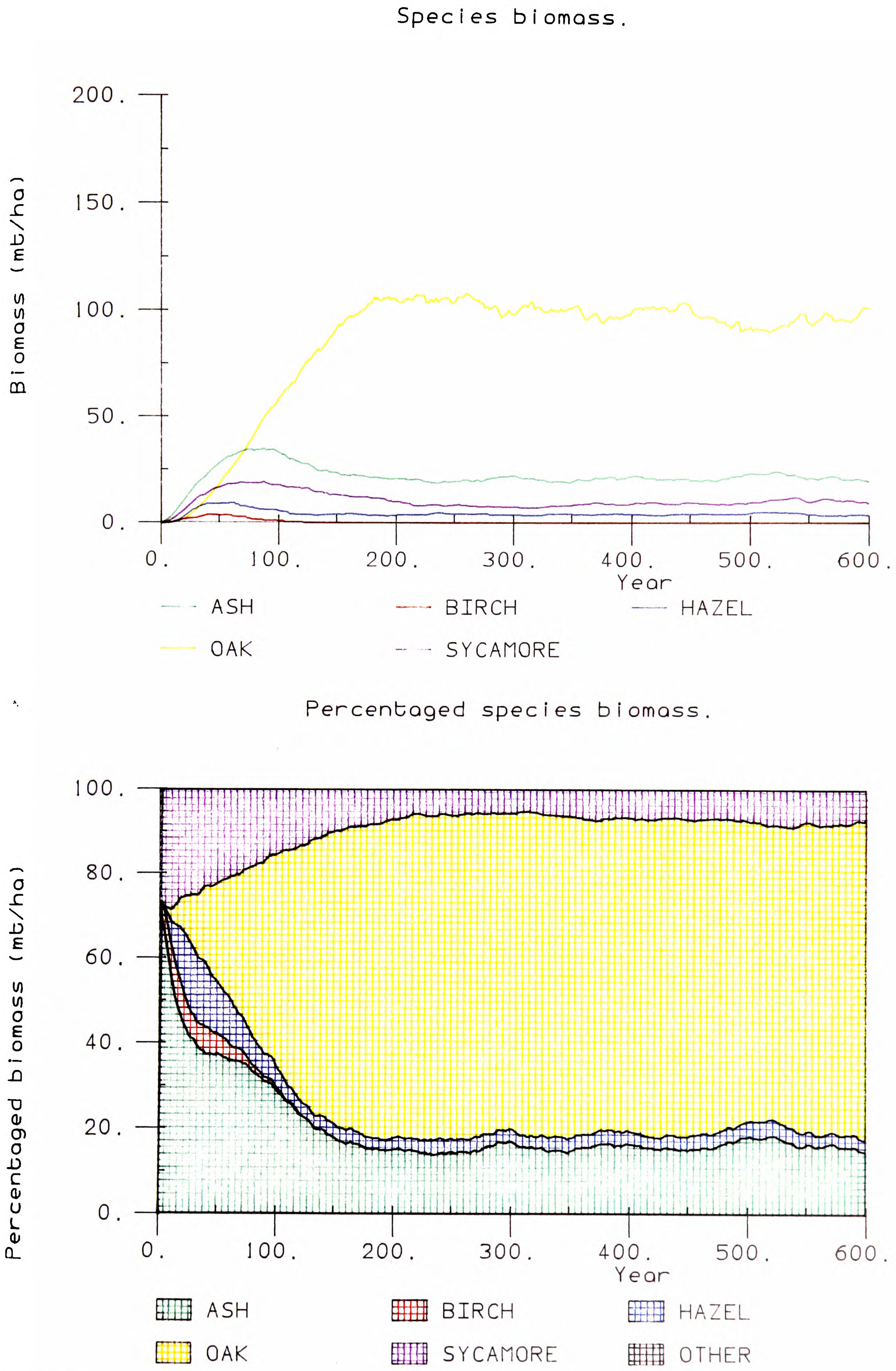


Figure 4.1. Biomass and percentage biomass for Meathop Wood. The result of 50 simulations from version of FORET developed by workers at ITE Merlewood. The old growth equations are used from the 'bare plot' version

the height-diameter equations necessitates alterations both to the values and the structure of the data file (PARAM_MEATHOP.DAT) required by all versions of the FORET program. The modified values are shown in Table 4.1. To accommodate the inclusion of extra variables required as a result of adding a new growth function, FORMAT statements and variables declared COMMON were altered in the program. This has been completed for new 'bare plot' and '1967 stand' versions of FORET.

Table 4.1. Parameters used in the data file PARAM_MEATHOP.DAT for FORET. For a full description of variables used in FORET see Appendix 1.

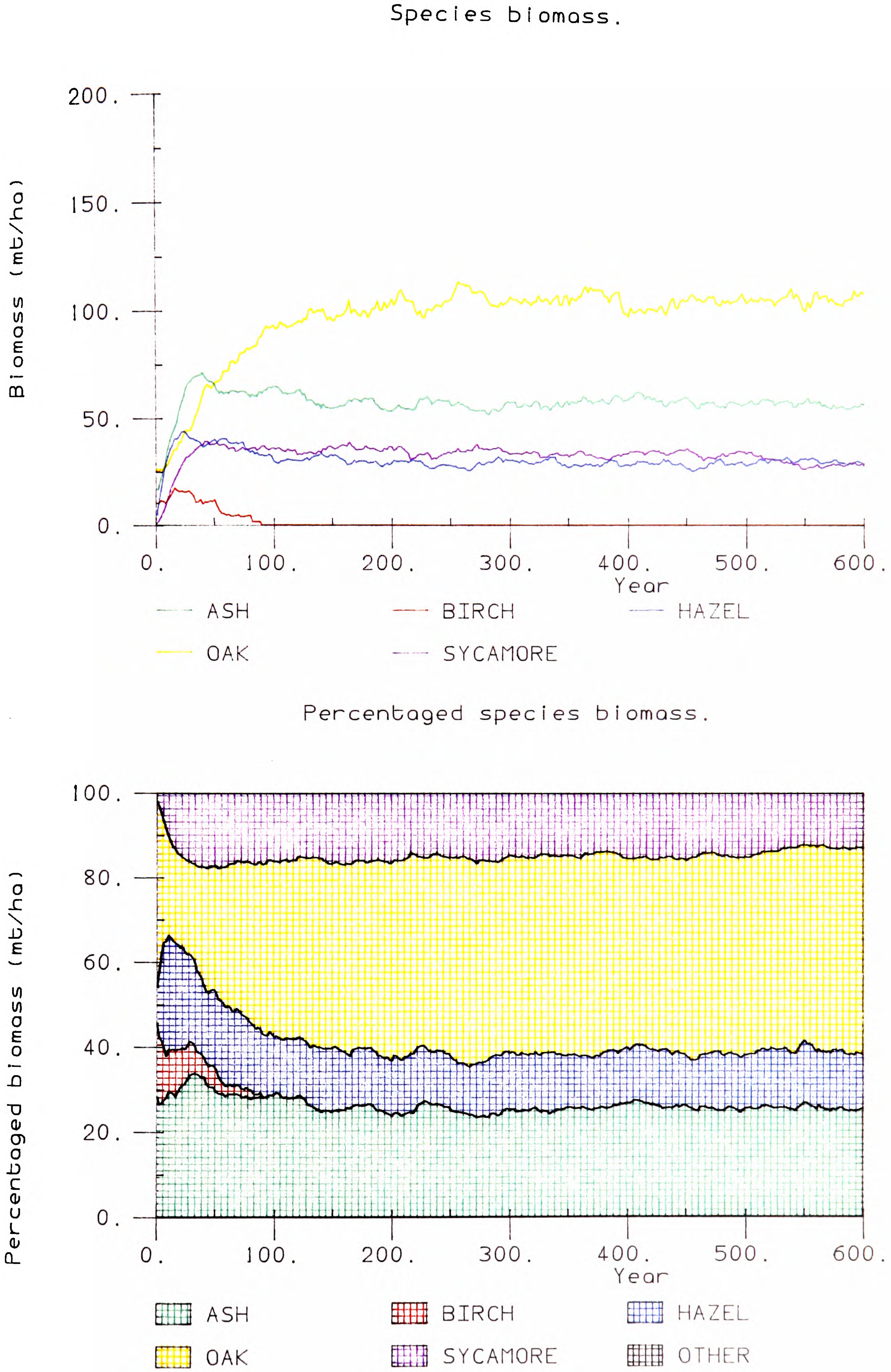
SPECIES	DMAX	DMIN	B3	B2	B1	ITOL	AGEMX	G	N-1	SPRTND	SPRTMN	SPRTMX	SWITCH	KTIME	NUM	DmHm
ASH	7375	1755	0.3348	1.436	1.865	1	200	2622	0.153	1	12	200	FFFFT	0	1	355000
BIRCH	6590	735	0.2698	1.215	2.026	2	90	2978	0.339	1	12	200	FTTFT	0	2	132000
HAZEL	6590	1251	0.2497	1.077	2.198	1	50	2870	0.300	3	1	200	TFFFT	0	3	132000
OAK	7375	1755	0.2792	1.274	2.025	1	300	1574	0.300	2	12	200	TFFFT	0	4	598751
SYCAMORE	7375	1755	0.2497	1.077	2.198	1	120	2916	0.207	2	12	200	FFFFT	0	5	364203

Hazel has not been considered in any of the studies presented in Chapters 2 and 3, but it is a common species in the lower storey of Meathop Wood. Therefore, rather than excluding it from the simulations, fairly arbitrary assumptions have been made regarding its rate and pattern of growth. It is assumed, owing to a lack of any published data on diameter increment, that its rate of growth is slightly slower than the values used for sycamore (ie a lower 'G' but the same leaf area exponent), and the maximum age of hazel is taken to be 50 years. These assumptions should, ideally, be substituted by values of parameters derived from field studies determined in the same manner as for the other species.

The error regarding the output of the diameter distributions was rectified but has highlighted other problems within the model which are best demonstrated by the results produced from simulation runs of FORET.

4.8 Simulations of forest development for Meathop wood.

A number of simulations were carried out using both modified 'bare plot' and '1967 stand' versions of the FORET model that include the new growth equations. Surprisingly, initial



Species biomass.

Percentaged species biomass.

Figure 4.2. Biomass plots for Meathop Wood. The result of 50 simulations from the `1967 stand' version of FORET using the new growth equations.

alteration of the growth equations had remarkably little effect on the overall predictions made by the model. Figure 4.2 shows the output of the '1967 stand' version of FORET: all parameters except those relating to the growth function are identical to the simulation shown in Figure 4.1. All model runs are based on 50 repeat simulations for a 1/12 ha plot, the output data are always the mean of the number of simulations.

4.8.1 Assessing the output from the model.

The current modified version of the '1967 stand' model produces two output files, A.DAT and DBH.OUT these can be used to produce the biomass and diameter frequency distribution graphs.

The graphs showing the diameter frequency distributions are more readily interpreted since they give more of an indication of the trends in the *structure* of the simulated forest. By examining diameter frequency distributions over time an idea of the *change* in the structure can also be determined, in terms of species, numbers of individuals, and their sizes. If parameters within the model are altered then the resulting changes are more readily identified by examination of these graphs. In contrast, biomass plots tell us nothing about the structure of the simulated forest, it is entirely possible that identical biomass curves for each species could result from the sum of very many small trees, rather than from an acceptably realistic diameter frequency distribution.

It should be stressed that the diameter distributions produced by published gap-models, both in their original and modified forms, have often been unrealistic and perhaps this is why published works present biomass curves only. Botkin *et al.* (1972) stated for the JABOWA model "the one difference found between predictions of the model and reports of real forests concerns the distribution of stems by size class". *For the purposes of forest management it is the distribution of the biomass in terms of stem size that is of critical importance.* Therefore, if this type of model is to be useful for investigating potential management scenarios, the problem must be tackled.

In the development of FORET for U.K. conditions this problem was resolved by empirical modification. Improvements in the interaction between the major modelled ecological processes made extensive use of the diameter frequency distributions.

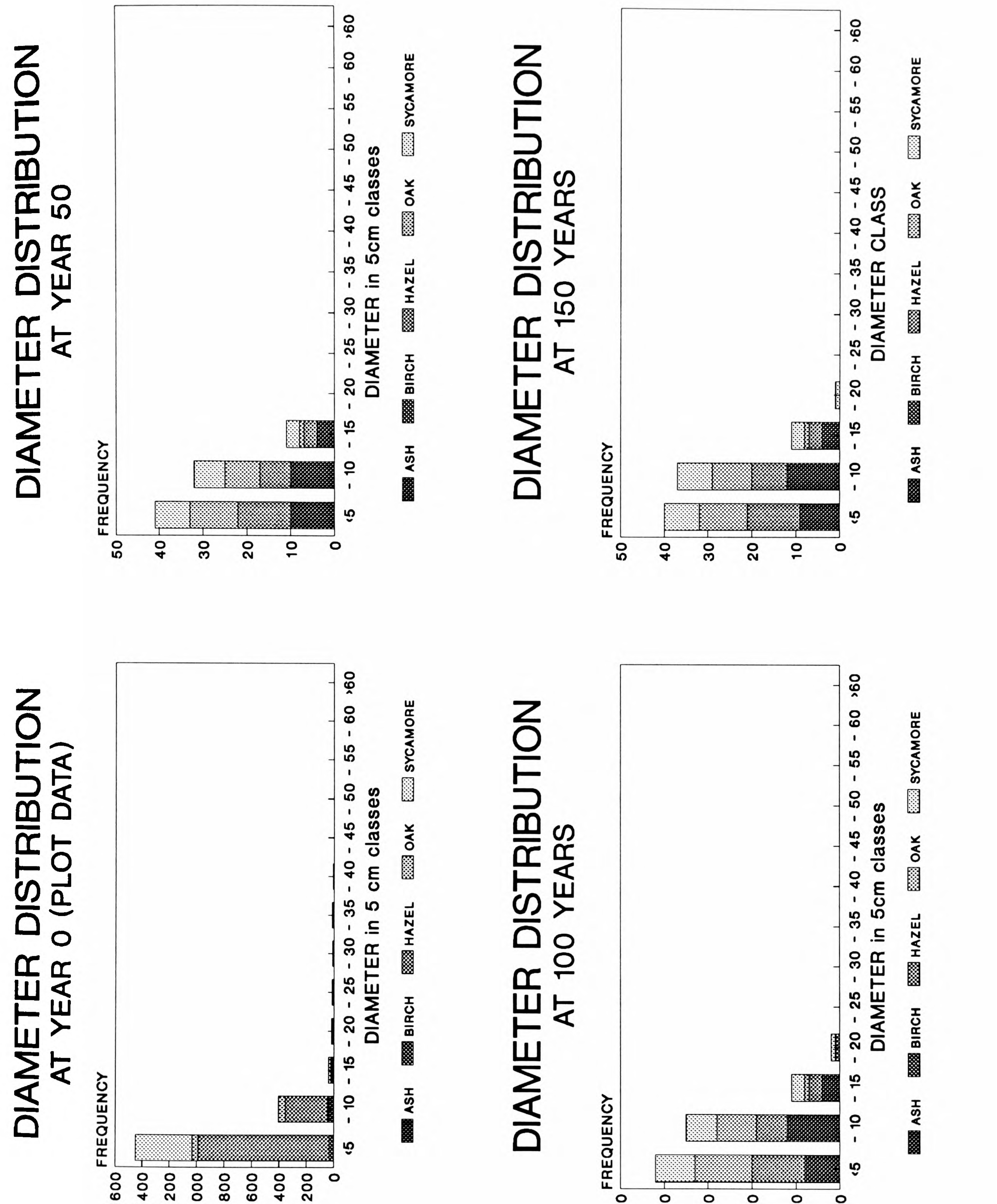


Figure 4.3. Diameter frequency distributions for Meathop Wood. The results from 50 simulations of the '1967 stand'version of FORET using the new growth equations.

4.9 Empirical alterations to the fundamental ecological processes.

The fundamental processes of regeneration, growth and mortality expressed within the model were behaving in a manner that would not be expected in a real forest. This was revealed by several investigative simulations of woodland development by altering a variety of parameters within the model. The diameter distributions produced by the model presented in Figure 4.3 show that trees over a dbh of 25 cm are rarely, if ever, produced. This is clearly unrealistic.

One possible explanation is that the mortality function may be acting incorrectly, causing tree death too early. This hypothesis was investigated by simulating forest growth with a reduced likelihood of death for slow growing trees (1 per cent chance of surviving 10 years). Trees previously exposed to a greater probability of dying if their increment fell below 1 mm per annum were not subject to the higher mortality probability until their annual increment fell below 0.01 mm. For trees growing at more 'normal' rates the mortality was also reduced (50 per cent chance of death before the maximum age). Even altering both of these fundamental mortality functions *simultaneously* resulted in very little change in the frequency distribution of tree diameters over time. Mortality *per se* was therefore unlikely be the causal factor in producing an unrealistic diameter frequency distribution.

4.9.1 Investigating growth multipliers.

Another potential explanation for the abnormal diameter frequency distribution is linked to the growth multipliers. These may act on the growth function to reduce the growth of each individual to an unrealistically low level. Consequently trees may never reach a large size because the effects of the simulated competitive and environmental interactions are grossly exaggerated. To test this hypothesis, the model was temporarily altered to remove the effect of the growth multipliers, by setting their value to 1 in the growth subroutine. This removed the constraints of a limited biomass for a given site, and all other aspects of competitive interaction.

In effect, then, many parameters were simultaneously altered to test the general sensitivity of the model to the growth multipliers. The resulting diameter frequency distribution was again

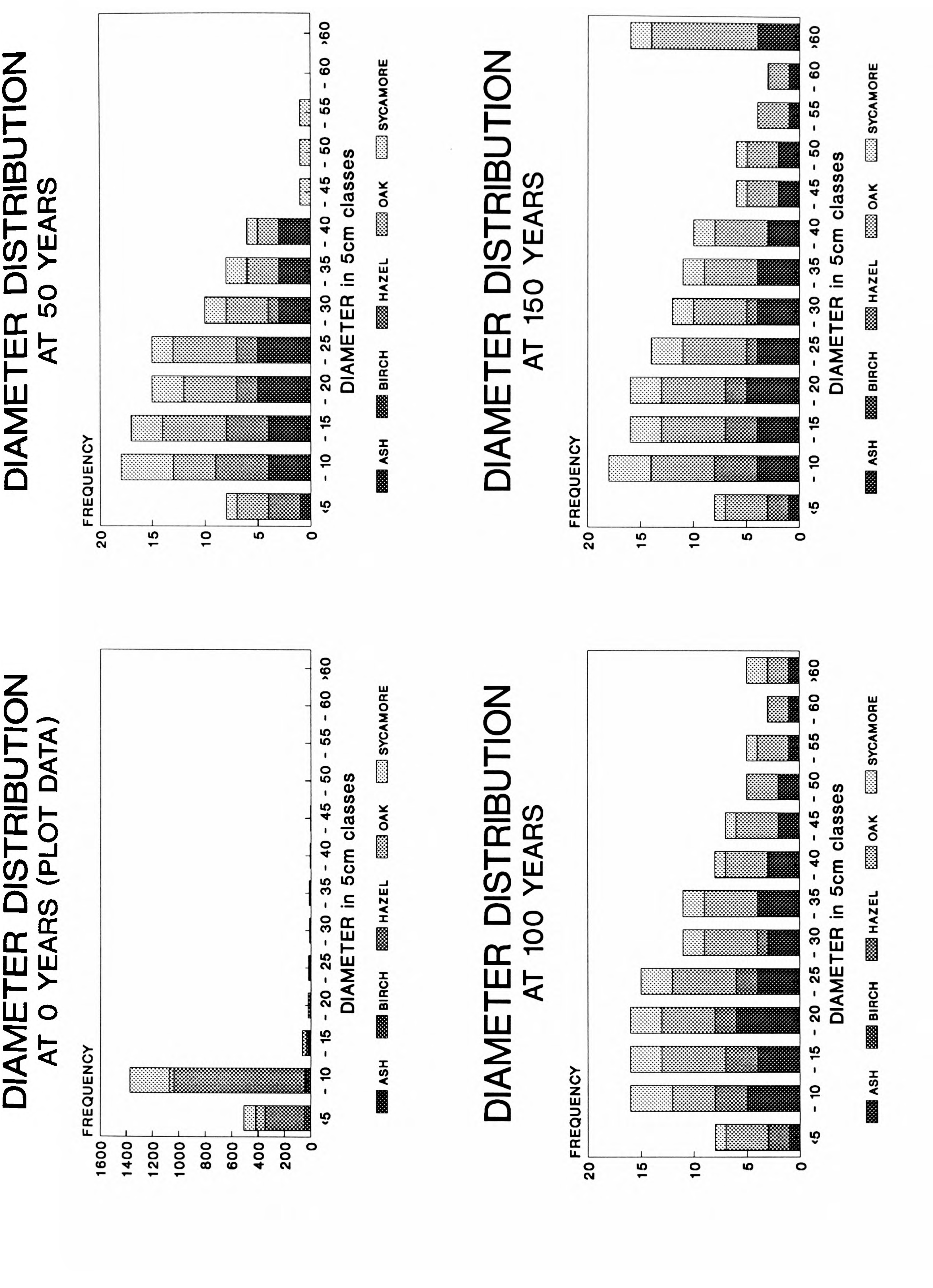


Figure 4.4. Diameter frequency distributions from the '1967 stand' version of FORET, for 50 simulations. **No growth multipliers were used.**

unsatisfactory (Figure 4.4). As the stand develops trees progress through the diameter classes, and there appears to be no limit to the number of large trees that a 1/12 ha plot can support. At 150 years there are 16 trees of over 60 cm dbh. However, the fact that all classes of diameter were represented, demonstrated that the output of the model is highly dependent on the behaviour of the growth function in association with the growth multipliers. It is therefore likely, given that the growth function had been thoroughly tested already, that the growth multipliers were responsible for the general inaccuracy in the diameter frequency distributions.

To investigate the specific importance of the multipliers, each was tested by removal of the others. The development of the diameter frequency distributions over time could then be examined and compared with the output from the simulation made in the absence of all growth multipliers (Figure 4.4).

When the species specific temperature limits on growth multiplier was tested alone, it allowed a slow increase in diameters but, on average, only one individual managed to attain a diameter of 50 cm in 200 years, and all smaller diameter classes were present at all times. This multiplier limits the growth of all individuals of a species equally, and growth seems to be reduced to an unrealistic level. In short, the temperature limits for tree growth make very little improvement to the output of the model, in terms of the diameter frequency distribution (Figure 4.5). This confirms the theoretical appraisal described in section 1.6.3.2 that this multiplier is only likely to be useful where a species occurs towards the margins of its geographical distribution.

Next, the light competition multiplier was tested in isolation. The resulting diameter frequency distribution (Figure 4.6) showed all classes of diameter developing over time. There is some indication that as the larger diameters are reached on a plot, the development of smaller trees is slowed. Species growth trends are not reduced to a level that trigger mortality (now reset to initial values) in conditions of high competition, and cannot be considered to represent all competitive interactions. However, this multiplier should be retained.

To test the biomass limiting/competition multiplier the light competition and temperature multipliers were removed. The output is shown in Figure 4.7.

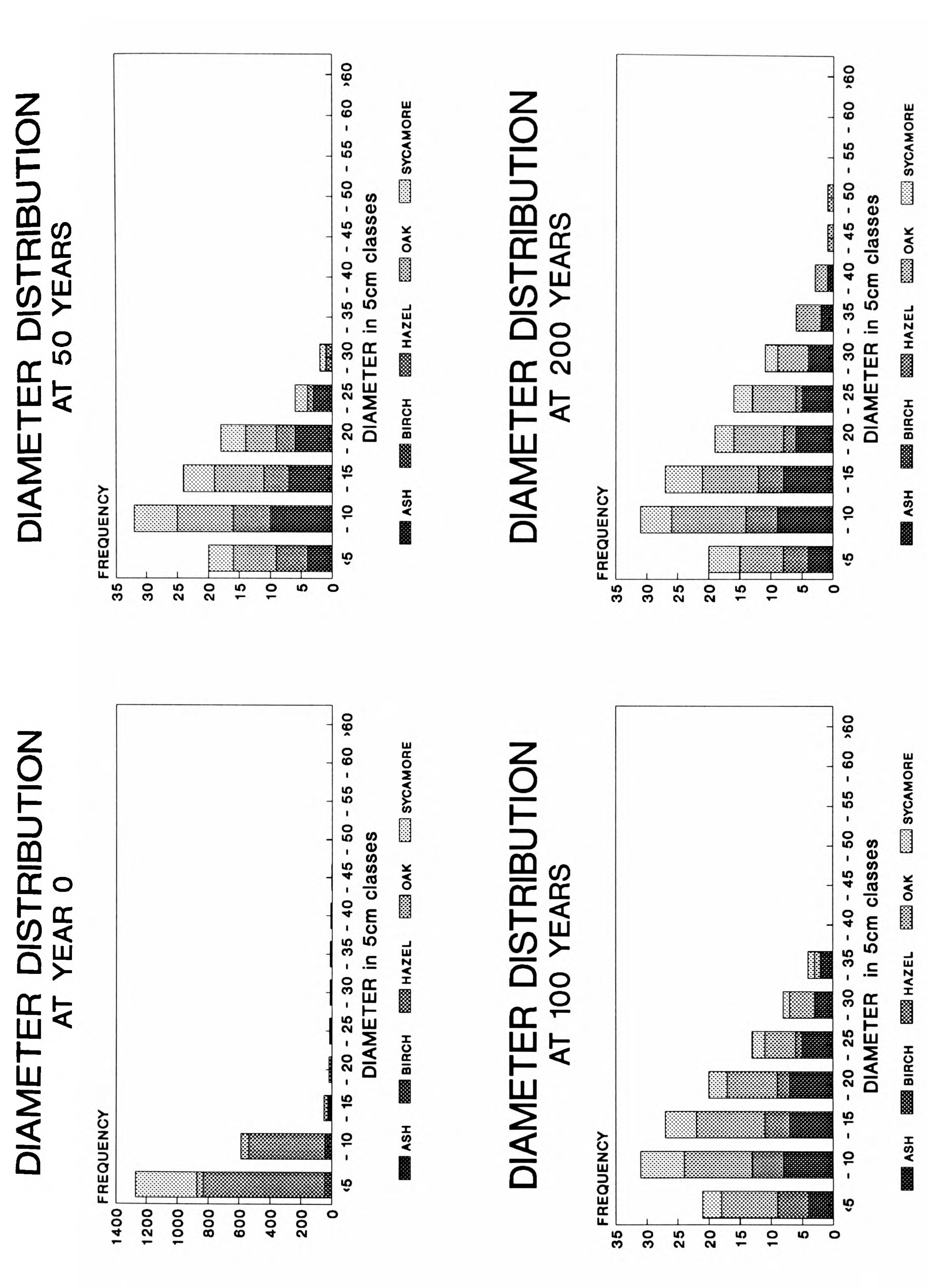


Figure 4.5. Diameter frequency distributions from the '1967 stand' version of FORET, for 50 simulations. **Only the species temperature limits growth multiplier was used.**

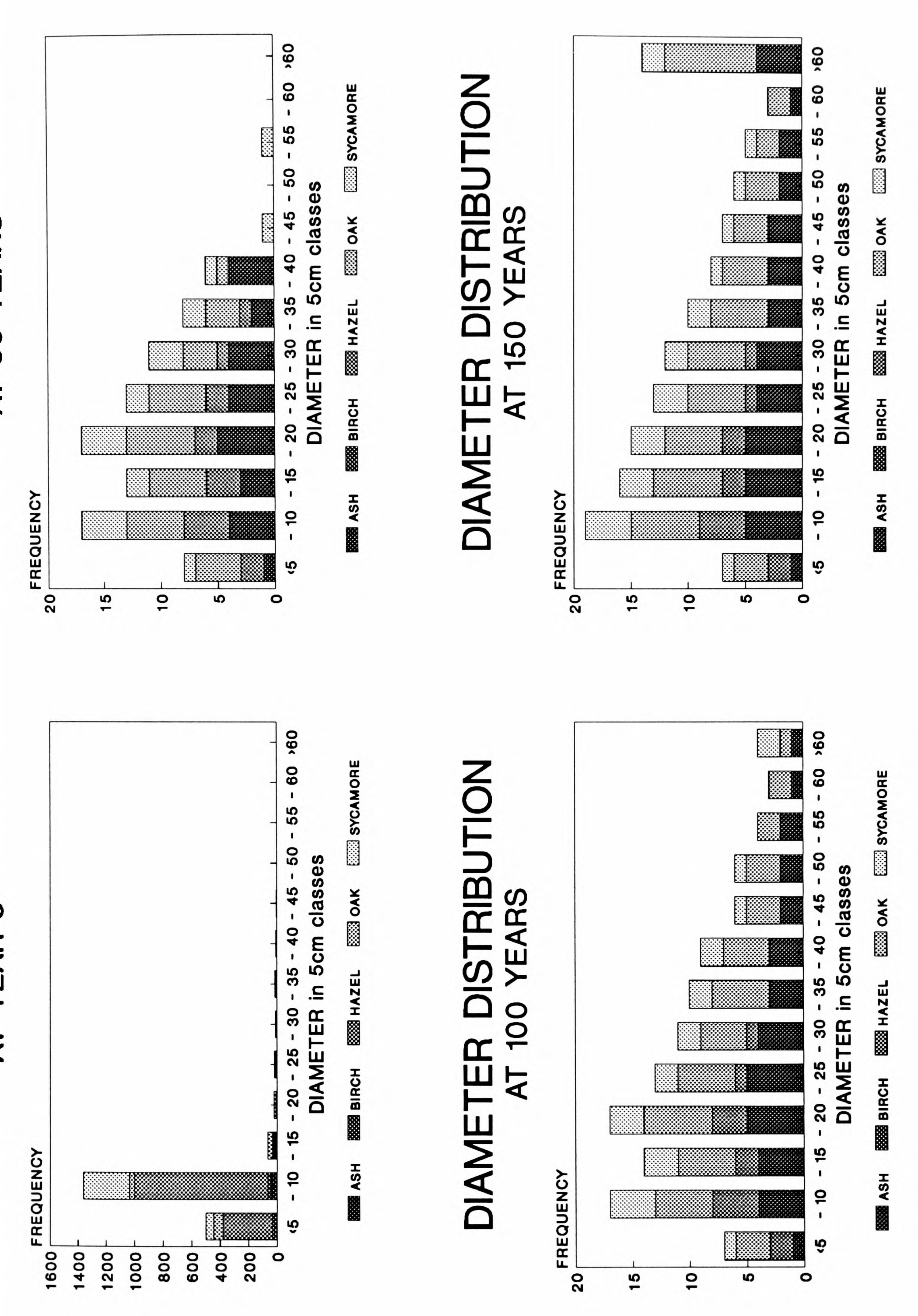


Figure 4.6. Diameter frequency distributions from the '1967 stand' version of FORET, for 50 simulations. **The competition for light was the only growth multiplier used.**

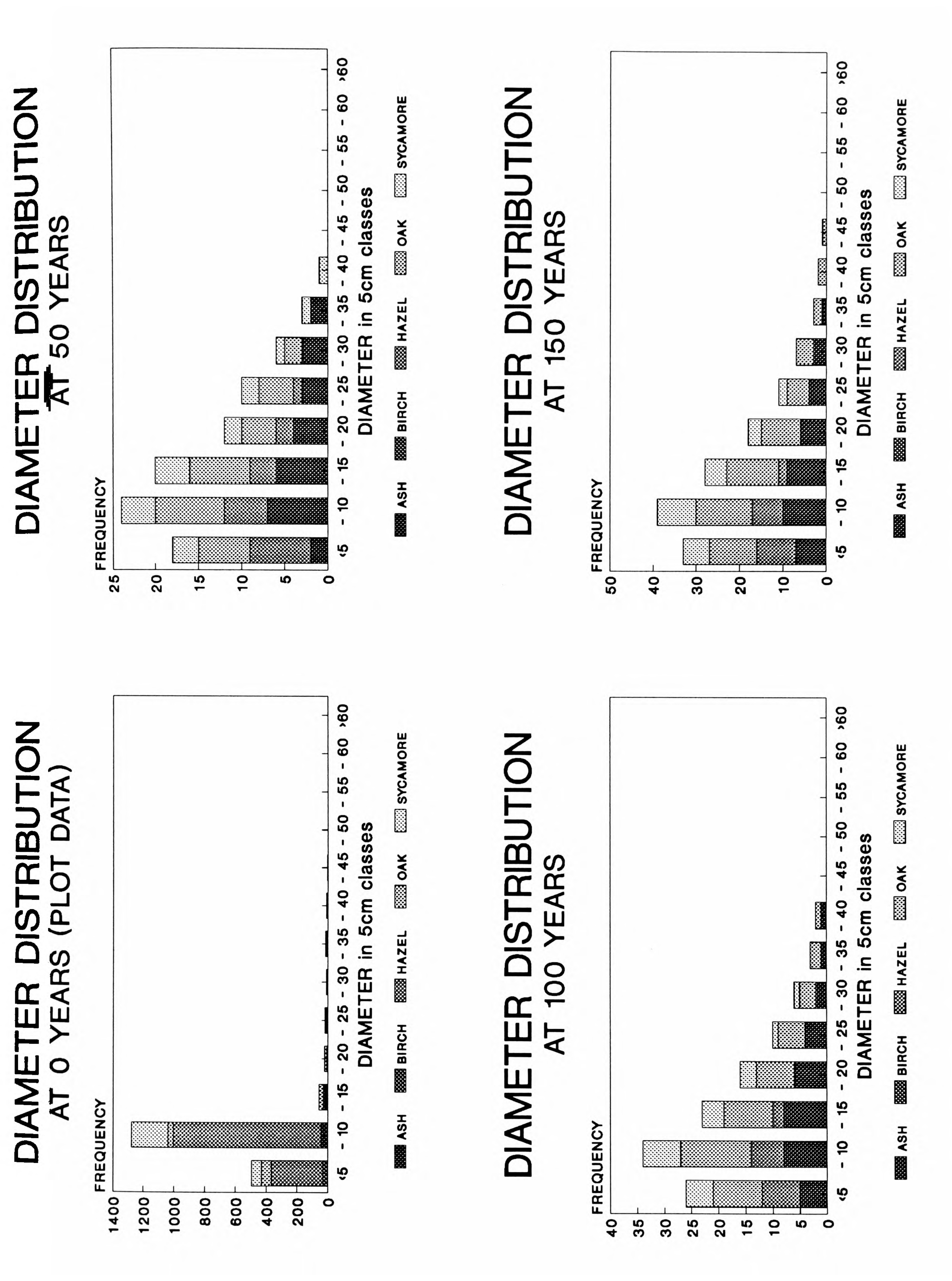


Figure 4.7. Diameter frequency distributions from the '1967 stand' version of FORET, 1/12 ha plot size for 50 simulations. **The competition/biomass limiting growth multiplier was the only one used.**

The diameter distribution shows two main points. Firstly, the biomass limitation/competition multiplier has a large effect on the diameter frequency distribution and is likely to limit the growth of individual trees (compare Figure 4.3 and 4.7 where this multiplier is absent). This growth reduction is of sufficient magnitude to expose the individuals to the higher mortality probabilities, and also reduces the likelihood of individuals reaching the larger diameters because diameter increments are small. Trees do not achieve diameters greater than 45 cm. Some individuals would be expected to achieve this diameter after 150 years. Yield Class 6 oak has a *mean* diameter of 59.3 cm, from management tables (Hamilton and Christie 1971) for plantations, and the simulated plots often *start* with trees in the 40 cm dbh class.

Secondly, it is likely that *this multiplier will mask the effects of other multipliers*. It was stated in section 1.6.3.3. that this multiplier acts to reduce growth of all individuals equally irrespective of their size and it was suggested that, in reality, larger trees are better able to compete for a limiting resource. The effect of other multipliers is to reduce growth still further, after the biomass limiting/competition multiplier has acted.

The contention that the biomass limiting/competition multiplier might mask the effect of the light multiplier was shown to be correct by examining the effect of a simulation using only these multipliers. The species specific temperature limits multiplier was removed from the model. The light competition and biomass limitation multipliers were included in their original forms. This resulted in a return to a similar diameter distribution to that produced in the first simulations (eg Figure 4.3), with trees over 25 cm dbh absent from the distribution, even after year 150.

This tendency to mask the effect of growth trends generated by the growth equation explains why the initial substitution of the new growth equations into the model produced very little alteration in the output of the model. Clearly, a new multiplier to encompass more realistic ideas concerning competition is required.

4.9.2 A new multiplier for competitive interactions.

When the total biomass on the plot is low, competition for space and resources is also assumed to be low. However, if total biomass on an area is high, it is assumed that the competition for space and other resources will also be high. Nevertheless, larger trees are likely to compete for limited resources more effectively until the maximum site biomass is reached. Given these assumptions, the new multiplier must reduce the growth rate of very small trees by a small amount if competition (biomass on the plot) is low, and by a large amount if competition is intense. Large trees should remain relatively unaffected irrespective of the level of competition. Intermediate sized trees should be less affected than very small trees by higher intensities of competition, but less able to compete than the very large trees. However, at low levels of competition growth should hardly be reduced at all. Therefore, the new multiplier, S(BAR), suggested for testing is;

$$S(BAR) = 1 - (BAR/SOILQ).(1-((D.H)/(D_m.H_m)))$$

where; BAR = total biomass of the plot, SOILQ = the maximum biomass allowed per plot for the forest type, D_m and H_m are species maximum height and diameter respectively, D = diameter of the tree, and H = height of the tree.

A more generalised expression of this multiplier is useful to understand its properties.

MULTIPLIER = 1 - (COMPETITION INDEX x (1 - TREE SIZE INDEX))

Where a competition index of 1 = high competition, and a size index of 1 = a large tree (for the species). A multiplier of 1 will not affect growth rates, but a lower one will reduce potential growth as shown in Table 4.2.

Table 4.2. The values produced by the new individual tree growth multiplier for a range of values for the tree size and competition level indices, shown in brackets.

	Competition Index		
Tree size index	High (1)	Medium (0.5)	Low (0.1)
Large tree (1)	1.0	1.0	1.0
Intermediate tree (0.5)	0.5	0.75	0.95
Small tree (0.1)	0.1	0.55	0.91

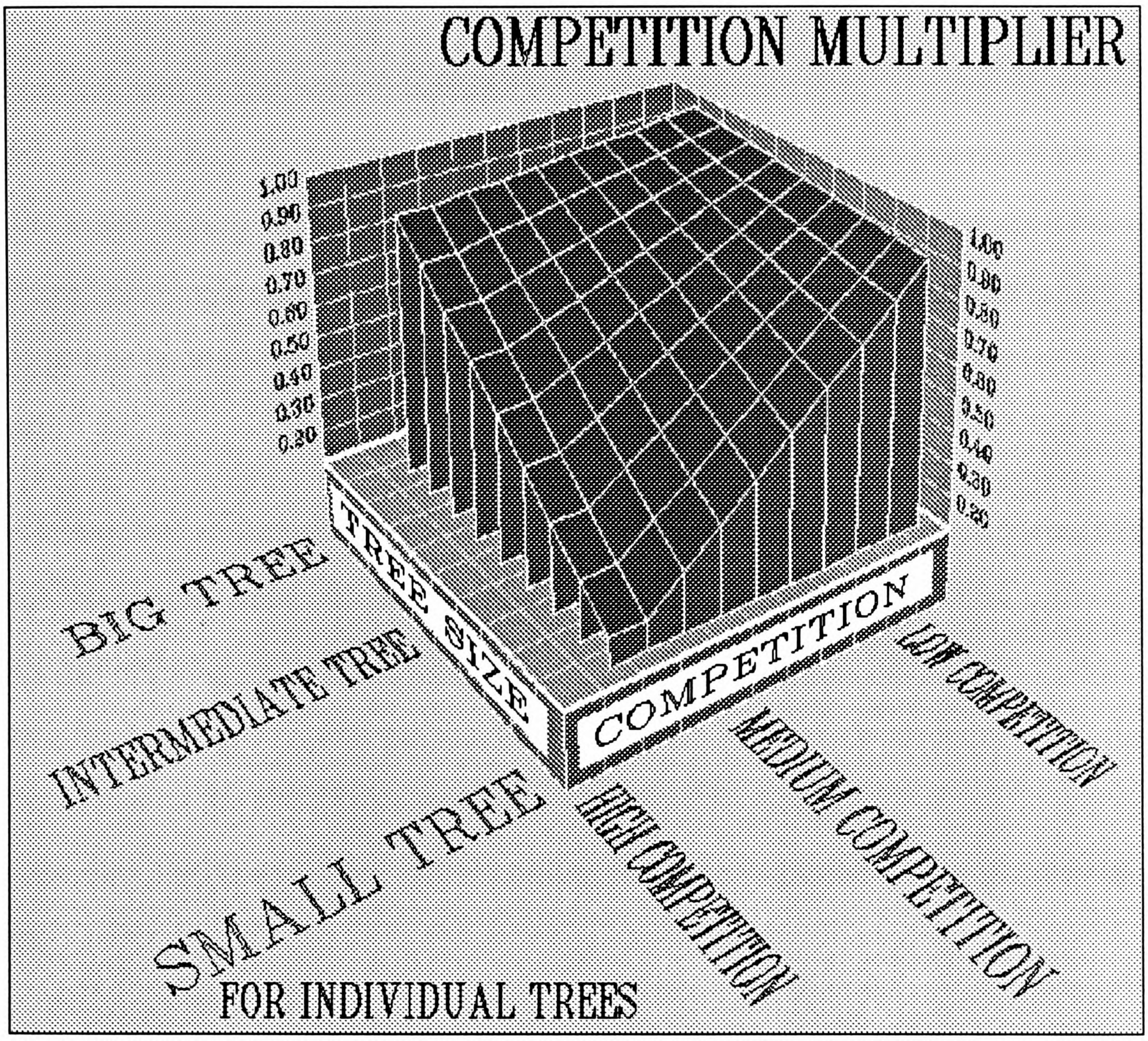


Figure 4.8. Values produced by the new competition multiplier (vertical axis) for varying sizes of tree and varying intensity of competition. Values between 0.1 and 0.9 have been used for the size and competition indices.

It should be noted that the biomass allowable on a simulated site is no longer directly limited by the field measurement if this multiplier is applied. If the biomass on a simulated plot is approaching the maximum recorded for the real site, a large tree can still grow with little hindrance by the growth multiplier (Figure 4.8). Under these circumstances it was hoped that the patterns of growth described by the new growth equation in combination with the mortality functions would tend to prevent large overestimations of total biomass.

When the multiplier was re-written in FORTRAN and substituted into the growth subroutine of the model, the resulting diameter distribution showed a more realistic pattern. The multiplier favours the larger trees in the competition for space and limiting resources. Figure 4.9 shows that as larger trees develop a reduced number of smaller trees remain in the simulated plot, and that once a large tree becomes established on a plot it will tend to retain its position of competitive dominance.

The next simulation re-introduced the multiplier for light competition which favours the taller trees over the shorter ones. This multiplier reinforces the advantage of an individual that becomes dominant on a plot. The results in Figure 4.10 show that at 100 years two large ash are dominating the 1/12 hectare plot, but that after 150 years a large oak has superseded the ash as the dominant tree on the plot. Since these data represent the mean of 50 simulations (equivalent to the mean data for 50 measured sample plots), it can be regarded as a general trend for the woodland.

Figure 4.10 shows the starting plot values through to the stage of development at 150 years. The published details for Meathop Wood (Reichle 1981) state that in 1967 there was an average stocking density of 759 stems per hectare, whilst the 1967 data from the model indicates a stocking density of approximately 1850 stems per 1/12 ha. There is therefore an error either in the values supplied or in the way that the data is read into/out of the program. However, it is interesting to note that after 150 years the model predicts 37 stems per 1/12 ha or 444 stems per hectare (average from 50 simulations), and this indicates a tendency to stabilise at sensible values. Further simulations, designed to test aspects of the program code, traced the error for the initial diameter frequency to the same source as the first frequency distribution error. The year 0

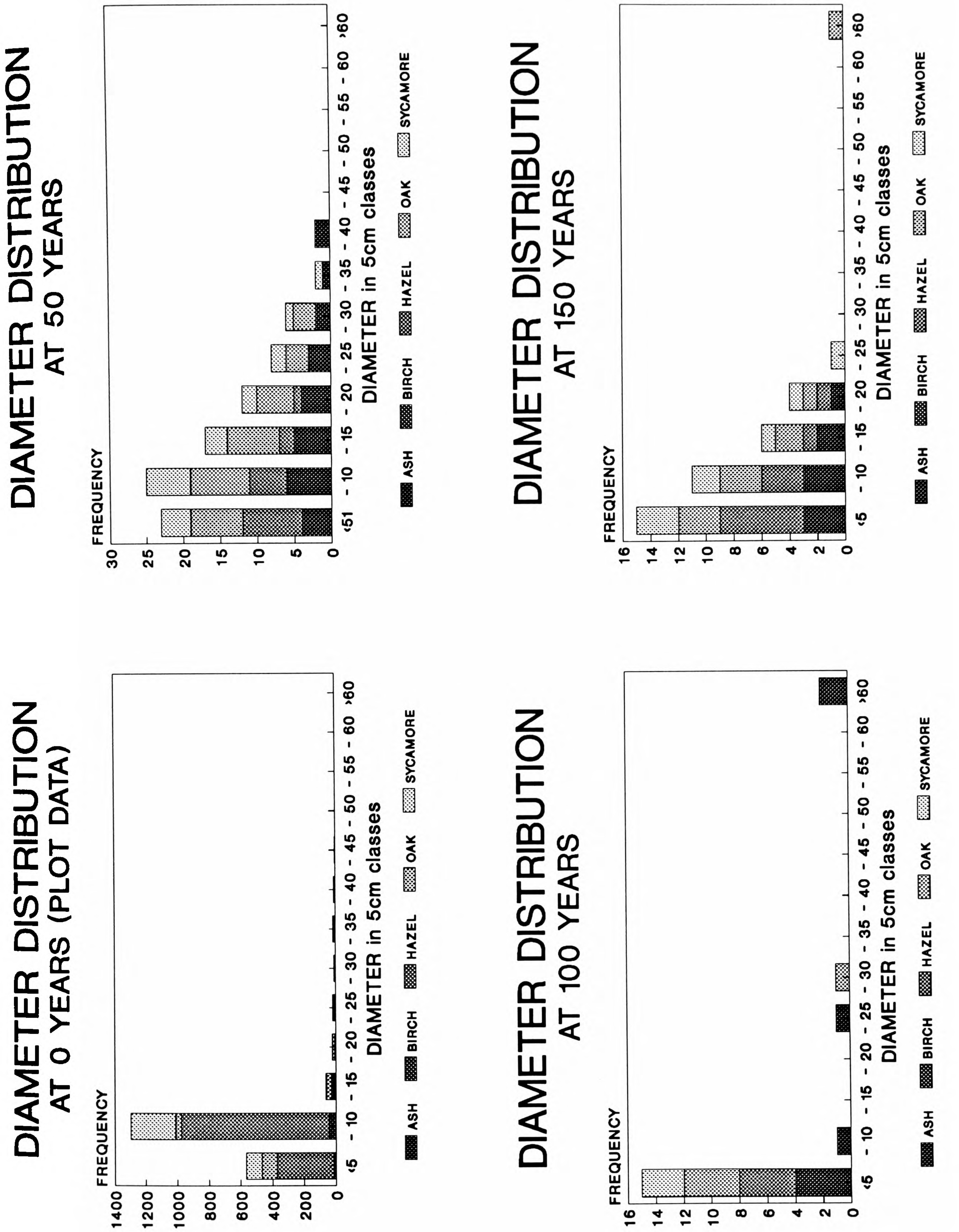


Figure 4.9. Diameter frequency distributions from the '1967 stand' version of FORET, the mean of 50 simulations for a 1/12 ha plot size. **The new competition multiplier was the only one used.**

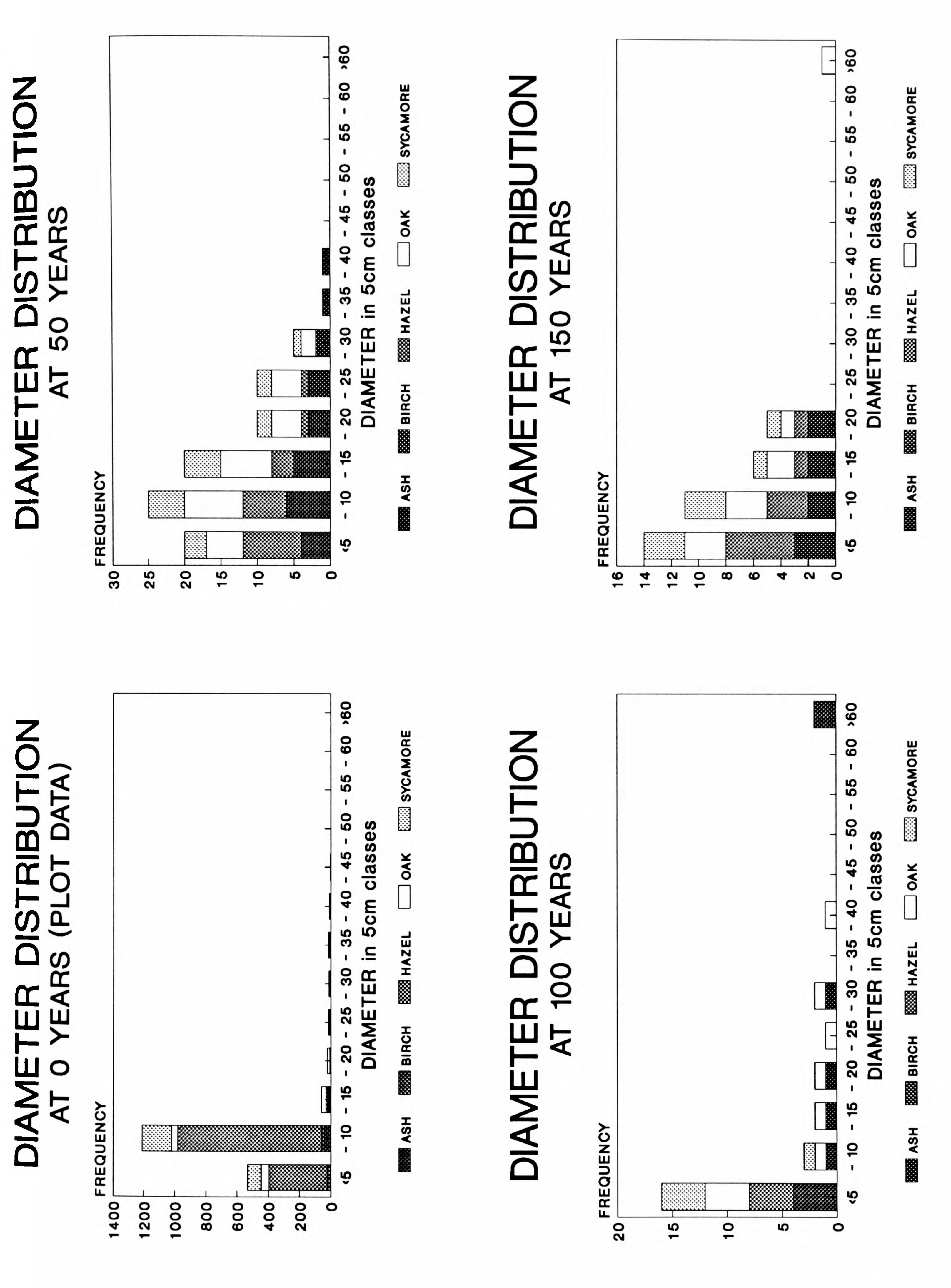


Figure 4.10. Diameter frequency distributions from the '1967 stand' version of FORET, the mean of 50 simulations for a 1/12 ha plot size. **The new competition and the light competition multipliers were used.**

starting plot values were being accumulated for each simulation. It might, therefore, have been expected that all the diameter frequency data for year 0 would be directly divisible by the number of simulations. However, this is not the case because the input plot data for year 0 is output from the model *after* the processes of regeneration, growth and mortality have acted. Year 0 is incorrectly labelled by the model and should be year 1 because the output data is the product of one year's simulated development, all subsequent years should consequently be re-labelled to a value of $n + 1$. An additional inaccuracy that has yet to be rectified is that the starting (field) data is still set for a simulated plot size of 1/100 hectare rather than 1/12 hectare.

4.9.3 The effect of growth multipliers on the biomass output.

The removal of the old biomass/limiting competition growth multiplier highlighted the sensitivity of the model to *any* parameter involved in the growth equation. However, the effects of this sensitivity were suppressed by the old multiplier. When all the growth multipliers were removed there was no limit to the maximum biomass on a plot, and even with the re-introduction of the light attenuation and new competition multipliers, estimations of plot biomass were still not specifically confined and as such resulted in the production of biomass estimates well in excess of the maximum recorded for Meathop Wood. This was due to the presence of large trees, and the absence of a multiplier acting to slow their growth as the simulated plot biomass exceeded the recorded site maximum. In addition biomass estimation, which is an exponential function that increases with increasing diameter, may well over-estimate for the larger diameters. The documentation that describes the biomass estimation function is not available and the limits for its application remain unclear. It is evident that modelling of mortality requires modification to provide better estimates of biomass, since the inaccuracy is caused primarily by a lack of control over biomass production.

4.9.4 Adjustment of mortality.

The main problem in constructing mortality functions, as with most other relationships within mixed-age, mixed-species woodland, is the lack of suitable data. The absence of data dictated arbitrary assumptions, based on a theoretical consideration of the likely effects of mortality.

This approach was adopted rather than taking the retrograde step of re-introducing the old competition multiplier in addition to the new multiplier (in a role that could be described as a biomass limiting multiplier). This would be a pointless exercise since the modelled tree growth would be limited by the most severe multiplier, ie the effect of the new competition multiplier would be masked by the old.

Since a large proportion of biomass would be accounted for by large trees (not particularly disfavoured by the new competition multiplier), it is likely that big trees will experience the stresses of site limitations via *mortality rather than growth reduction.* It was reasoned that in reality as a site approaches the maximum biomass it can support, the competition will increase dramatically. It is unlikely that all individuals will experience an equal reduction in their growth rates as competition increases, rather that large trees will be at a relative disadvantage because they have to support more living tissue, before being able to divert resources towards growth, than smaller trees. The result must be mortality if the site biomass maximum is exceeded.

This is akin to adopting the findings on self-thinning of Reineke (1933) and Yoda *et al.* (1963), but since these refer to even aged stands an empirical interpretation has been used. 'Self-thinning' is prompted by approaching the threshold of maximum biomass for a plot, and results in mortality. There are several assumptions that are implicit in the alterations made, and they concur with the studies by Hamilton (1990). Firstly, as biomass (or basal area) tends towards the site maximum, mortality will remove a greater proportion of the gross stand biomass increment. Secondly the higher rate of mortality that is known to apply to small trees is reinforced in the model by the new competition multiplier in association with the threshold for minimum diameter increment resulting in greater probabilities of mortality. Thirdly, if plot biomass is not approaching the maximum, a constant mortality for well established trees should still apply.

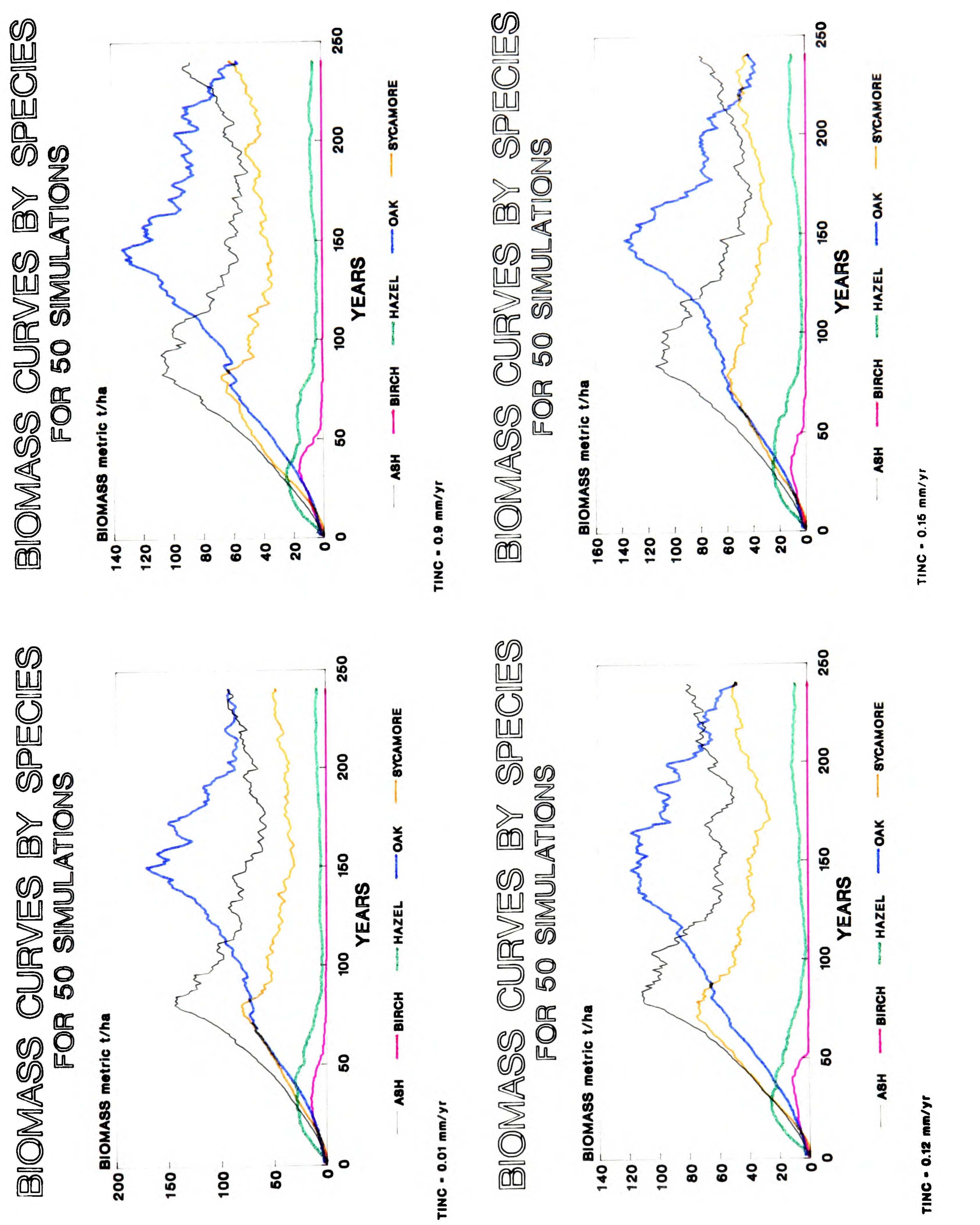


Figure 4.11. Biomass production by species, predicted from the '1967 stand' version of FORET, the mean of 50 simulations for a 1/12 ha plot size. Following the adjustment of mortality, the diameter increment threshold (TINC) for higher probabilities of mortality was varied in order to match predicted maximum site biomass to field data.

The threshold of diameter increment to trigger higher mortality required empirical matching to site quality to produce realistic biomass predictions. Alterations to mortality test the amount of biomass on a simulated plot against that allowable. If the ratio of the biomass present to that allowable exceeds 0.9 *and* an individual is greater than 60 per cent of the maximum possible size for the species then it is likely to be eliminated from the plot via exposure to high probabilities of mortality.

When the diameter increment threshold for exposure to higher probabilities of mortality (TINC) was varied between 0.01 mm per year and 2 mm per year, a value of 0.9 mm per year was found to be most suitable. Figure 4.11 shows four simulations with varying values for TINC. It can be seen that this variable can influence the biomass that is predicted. The value for TINC was selected on the basis of predictions from single simulations, such that values for maximum plot biomass transiently reach (or marginally exceed) the recorded value taken from Meathop Wood. Total biomass for Meathop Wood is approximately 328 metric tonnes per hectare. Obviously, the mean biomass predictions at any point in time will be lower than the transient maxima shown in single simulations.

4.9.5 Measured growth trends at Meathop Wood.

An obvious, and very important, question is to ask how well the predictions from the model compare with known measurements, and how realistic are the predictions of future forest development. In order to establish this there has to be some definite basis for comparison. Fortunately, recurrent inventory has taken place at Meathop Wood since 1967, and it is also known that the wood was cut-over in 1939 with the occasional large tree left standing. The wood is probably unique, as data for mixed deciduous, mixed-age woodland is exceptionally rare. It is not by accident that this woodland has been chosen to assess the results from FORET.

Sykes (1989) presents a description of the wood in 1967 and 1988, summarising the developmental changes that took place between these dates. The diameter frequency distributions (section 4.10, Figures 4.13 and 4.14) show the structure of the woodland in 1967 and 1988. Oak, ash, and birch shown net losses in the number of stems, whilst the sycamore

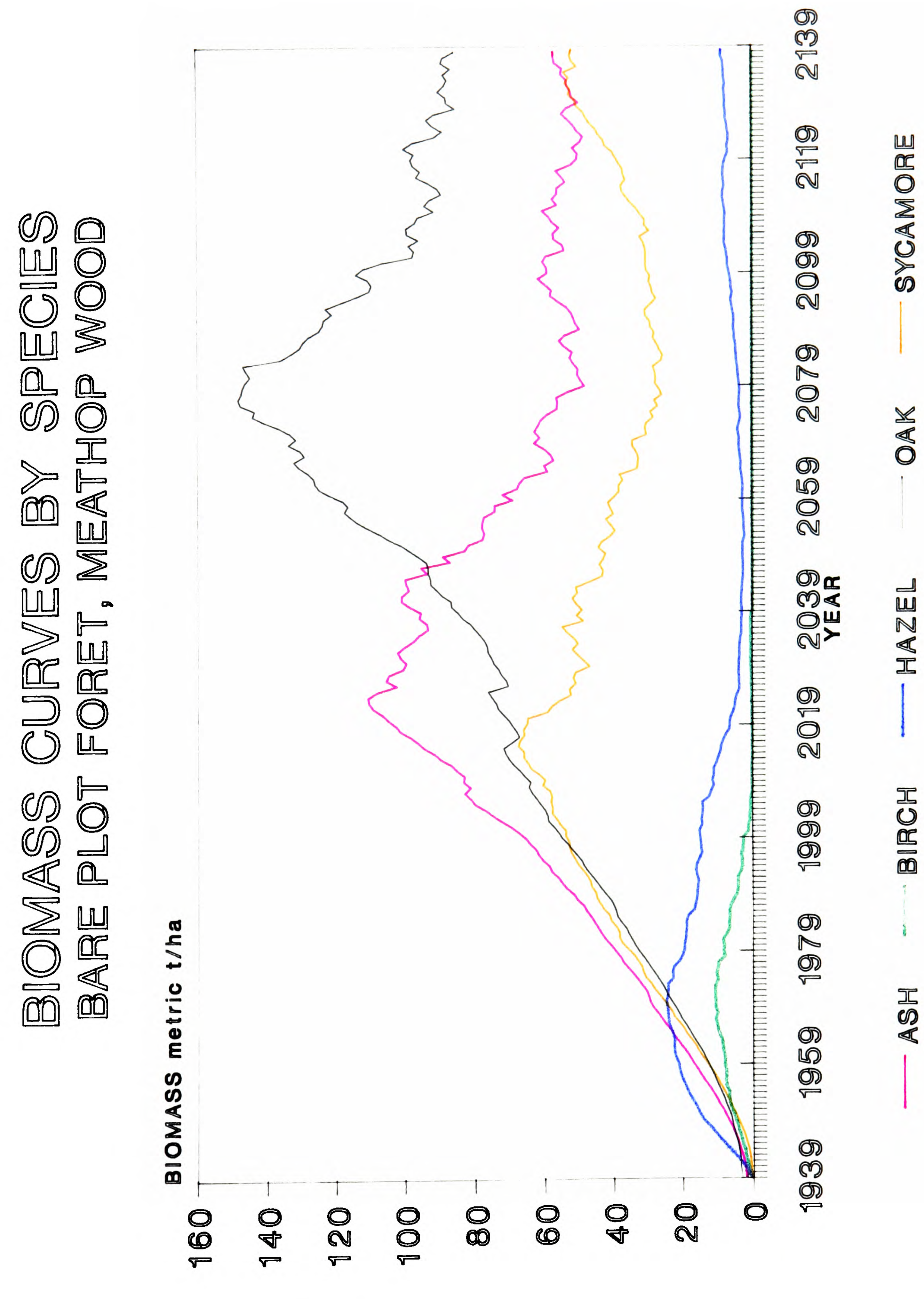


Figure 4.12. Biomass production by species, predicted from the 'bare plot' version of FORET, the mean of 50 simulations using a 1/12 ha plot size. The trends between 1967 and 1988 are a realistic representation of actual trends measured in Meathop Wood, Cumbria.

component almost doubled. Birch and sycamore showed opposite trends, birch produced negligible regeneration and 52 per cent of the original trees died. Sycamore doubled its net recruitment whilst only 24 per cent of the original trees died. The percentage of tree mortality was the greatest for birch.

4.10 A comparison of measured and simulated growth trends.

The general trends of woodland development in terms of biomass seem to follow this general pattern (Figure 4.12). Oak and ash predominate, and sycamore becomes more prevalent but not at the expense of oak and ash. Birch rapidly dies out and hazel, not included in the data presented by Sykes (*op. cit*), remains at a low levels of biomass at a fairly constant value. This would seem to agree with the general trends observed in the wood. However, a far more rigorous test is to compare the diameter frequency distributions (Figure 4.13). The starting point for the model is assumed to be 1939 when there were a few trees on each 1/12 of a hectare but the majority of the area is assumed to be cut-over. To simulate this the tree data for 1/100 ha plots were used as the starting points for 1/12 ha plots. This is assumed to represent the stand as it would have been in 1939. The model was modified to produce diameter frequency data for the years corresponding to 1967 and 1988.

The results from this showed a good similarity between the actual data for 1967 and that predicted from the model. However the estimates that correspond to the 1988 survey are less representative of reality.

An alternative prediction was produced by running the 'bare plot' version of the modified FORET model. This assumes that no trees were present after the clear cut in 1939. The results can be seen in Figure 4.14. In this simulation the prediction for 1988 is closer to reality than the 1967 estimate. For all but the smallest trees, the 1988 estimate is quite realistic. Perhaps the inaccuracy for the 1967 prediction is to do with the presence of the occasional large tree that remained on the site in 1939, altering the predicted early development as a consequence.

Common to both these predictions is the significant modelled recruitment between 1967 and 1988. The difference between predicted development and the reality is almost certainly

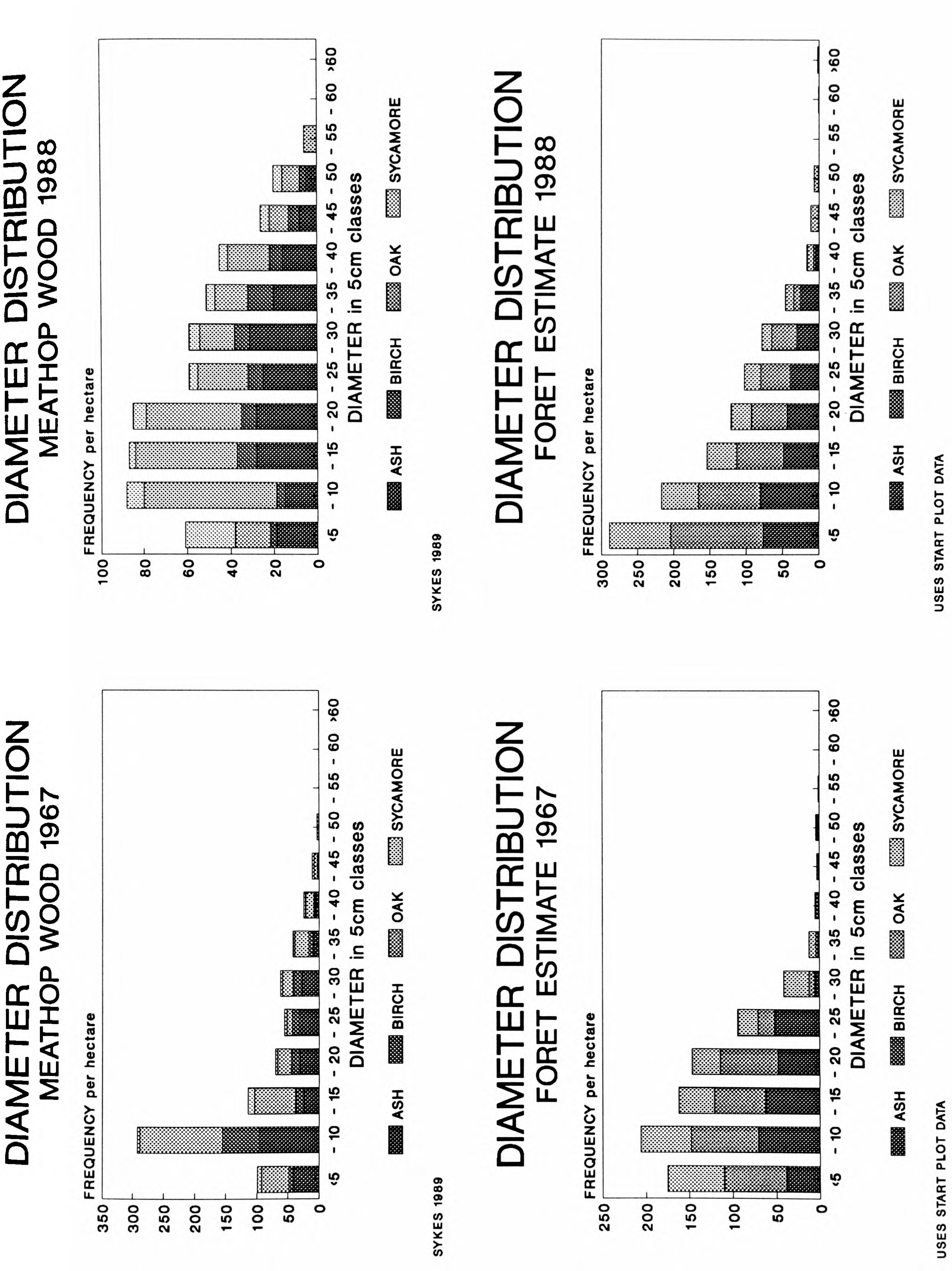


Figure 4.13. Diameter frequency distributions from measurements taken at Meathop Wood in 1967 and 1988 (Sykes 1989) and predictions from the '1967 stand' version of FORET for the same years. The simulation starts in 1939 with a few trees on each modelled plot, 12 simulations produced a diameter distribution per hectare.

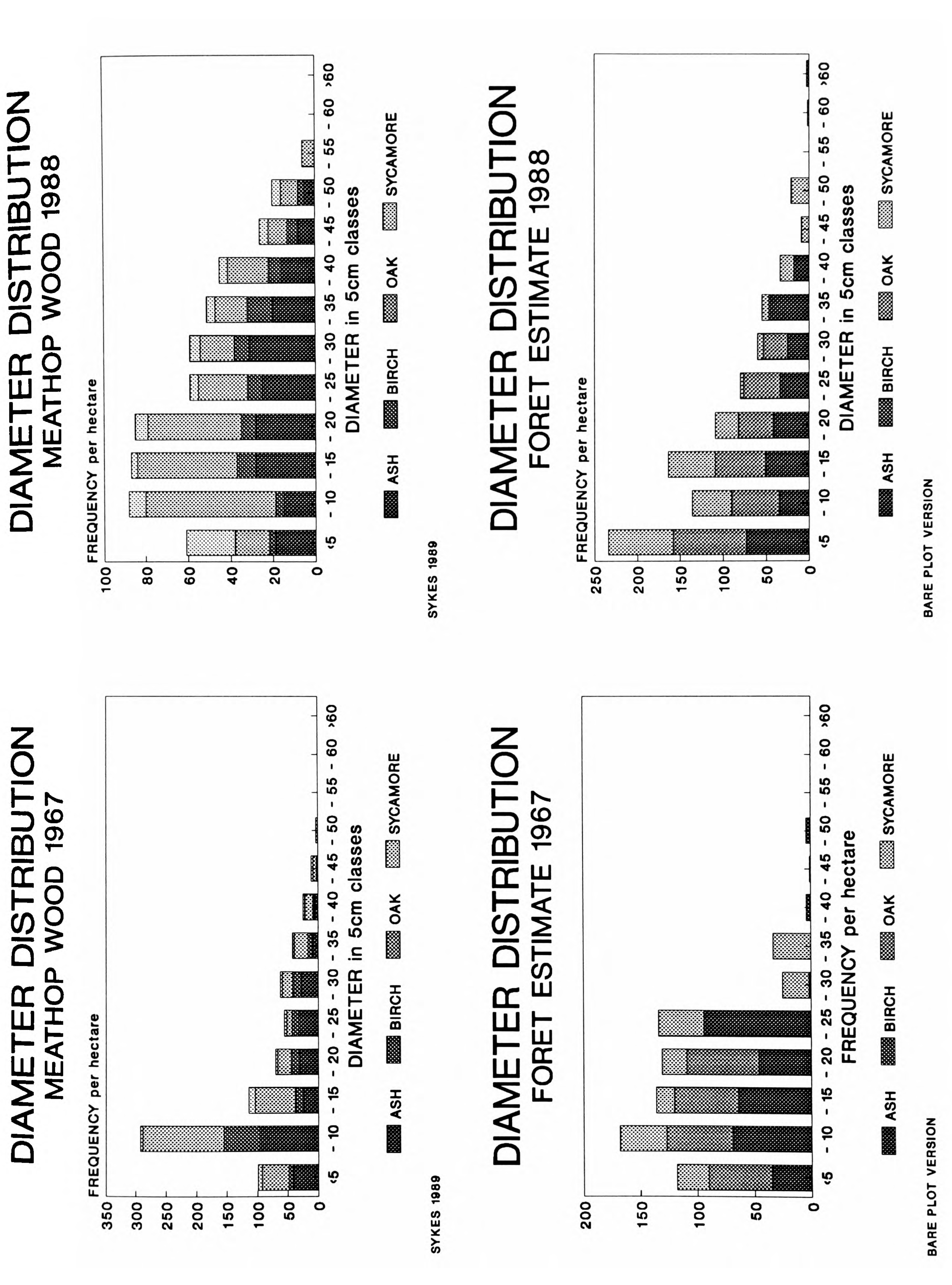


Figure 4.14. Diameter frequency distributions from measurements taken at Meathop Wood in 1967 and 1988 (Sykes 1989) and predictions from the 'bare plot' version of FORET for the same years. The simulation starts in 1939 with no trees on each modelled plot, 12 simulations produced a diameter distribution per hectare.

connected with the assumptions regarding regeneration, which have remained largely unaltered from the original published version of FORET.

4.10.1 Alteration of regeneration.

Regeneration in the FORET model can be described as the introduction of new trees to the plot. The new trees have an average diameter of 1.27 cm dbh and cannot, strictly speaking, be the result of the current years germination.

An attempt was made at altering the regeneration routine to produce a better representation of the likely conditions at Meathop. The original FORET model included a subroutine that allows 'dead' tree stumps (ie those eliminated by mortality) to sprout new shoots. This is apparently a common form of natural regeneration for the southern Appalachian forests of the U.S.A. However, apart from deliberate coppice management, it is assumed that this is less likely to be the case for the U.K. The SPROUT subroutine was therefore eliminated from the model. Although it affects many parameters in the model, the results from repeated simulations to predict the development of Meathop Wood were hardly altered.

Regeneration of seedlings is controlled by a number of tests or 'switches' that check the eligibility of each species to regenerate against defined climatic and site factors, but the net number of seedlings is increased until the leaf area of the plot has reached a pre-defined level. This level has remained unaltered, even when workers at Merlewood changed to a 1/100 ha plot size. The way in which leaf area is used in regeneration requires further study, but preliminary investigation, shows that it has very little effect. The rate of regeneration is largely determined by the values produced by a random number generator. However an idea of maximum leaf area for a site may be one way in which the rate of regeneration could better reflect reality.

There is some evidence to suggest that complex regeneration mechanisms may act when stands are not artificially regenerated. For example there is a tendency for sycamore to regenerate under ash, and *vice versa* , and there are other similar relationships (Watt 1925, Taylor and Davies 1985). In short, the study and application of regeneration ecology will be very important in the further development of gap-models.

4.11 Single simulations versus multiple simulations.

It has become common in published literature from simulations using gap-models to present the mean data from multiple simulations. Botkin *et al.* (1972) Shugart and West (1977) both use 100 repeat simulations, whilst Bormann and Likens (1979) recommend 200 repeat simulations. The rationale for this has often been to provide 'general trends' in the development of the simulated forest. Gap-models aim to capture some of the stochastic qualities of forest development but only over small areas of forest.

Multiple simulation of plots can be interpreted in two similar, but distinct, ways. Firstly, the mean data can be regarded as the developmental trends for an area equal to the total size of area modelled (plot size multiplied by the number of simulations), expressed in the output *per unit area of plot size* or, secondly, as the mean fate for a small area from a number of possible outcomes (different due to chance). The former interpretation is commonly assumed, but not clarified, whilst the second is overlooked. If a model is to be effectively verified and validated then this second interpretation is crucial. The stochastic behaviour of the model is more effectively investigated by consideration of many *single* simulations. The problems of over-estimation of biomass, errors in diameter frequency distributions, the adjustments made to mortality, and the introduction and testing of growth multipliers were all dealt with by consideration of single simulations in the first instance. It is only when the output from the model appears to behave as one might expect for the plot size, that multiple simulations were attempted. Trends from models such as these are only meaningful if each individual simulation is reliable.

Perhaps a more logical approach, once the model has been satisfactorily verified, is not to decide *between* single or multiple simulations, but to examine trends on the basis of the *spatial scale required.* If the diameter frequency and biomass data are not divided by the number of simulations, and merely summed, then the output *could* be interpreted as the trend for the area defined by the product of plot size and number of simulations. This automatically takes account of the changes that can be seen in the output when many simulations are used. One would expect that over a larger area the proportion of plots in an early stage of development due to the formation of a gap would be low and that the general levels of biomass over the area fairly constant (not widely fluctuating). Whereas, on a small scale the death of a single large tree would be readily apparent in a plot of biomass for the area, ie biomass fluctuations would be larger. Diameter frequency distributions would also be different depending upon the spatial scale. If a small area of forest is surveyed, it would be unusual to find a complete range of diameter classes, some would be expected to be absent or poorly represented. However, over larger areas in woodland that has not suffered large scale exogenous disturbance, all diameter classes would be expected and their frequency distribution may also be of a predictable shape. These effects can also be reproduced by consideration of different numbers of simulations to represent different spatial scales for output. This is possible because scale of the modelled interactions is set to represent the 'normal' dynamics of a 'natural' forest.

The objective of this work has been to strike a realistic balance between the modelled processes of regeneration, growth and mortality. The examination of individual simulations has been of particular value for this purpose. It should be noted that nature of disturbance to produce patches within mixed deciduous woodland is not always of identical magnitude to the chosen plot size of 1/12 hectare. However, this plot area has been selected to be of sufficient size, (section 1.7) to allow the scale of disturbance most often found in British woodland, and to match the maximum size of the trees that may grow within it.

4.11.1 Discussion of results from single and multiple simulations.

The results of multiple simulations have already been presented in Figures 4.13 and 4.14. Figure 4.15a shows a typical single simulation diameter frequency distribution for years 1, 51, 101, and 151. The simulated woodland shows a progression from a plot with only a few trees at year 1 (section 4.8.2), which allows a spurt of regeneration as well as growth that is not restricted by larger diameter classes. By year 101 the numbers have reduced and the spread of diameters is greater, two ash stems and one oak have reached the largest diameter class, and at 151 years the biomass is concentrated in three oaks all over 60 cm dbh with eight stems below 5 cm dbh. After 201 years (Figure 4.15b) one of the large oaks has died and there has been an increase in the

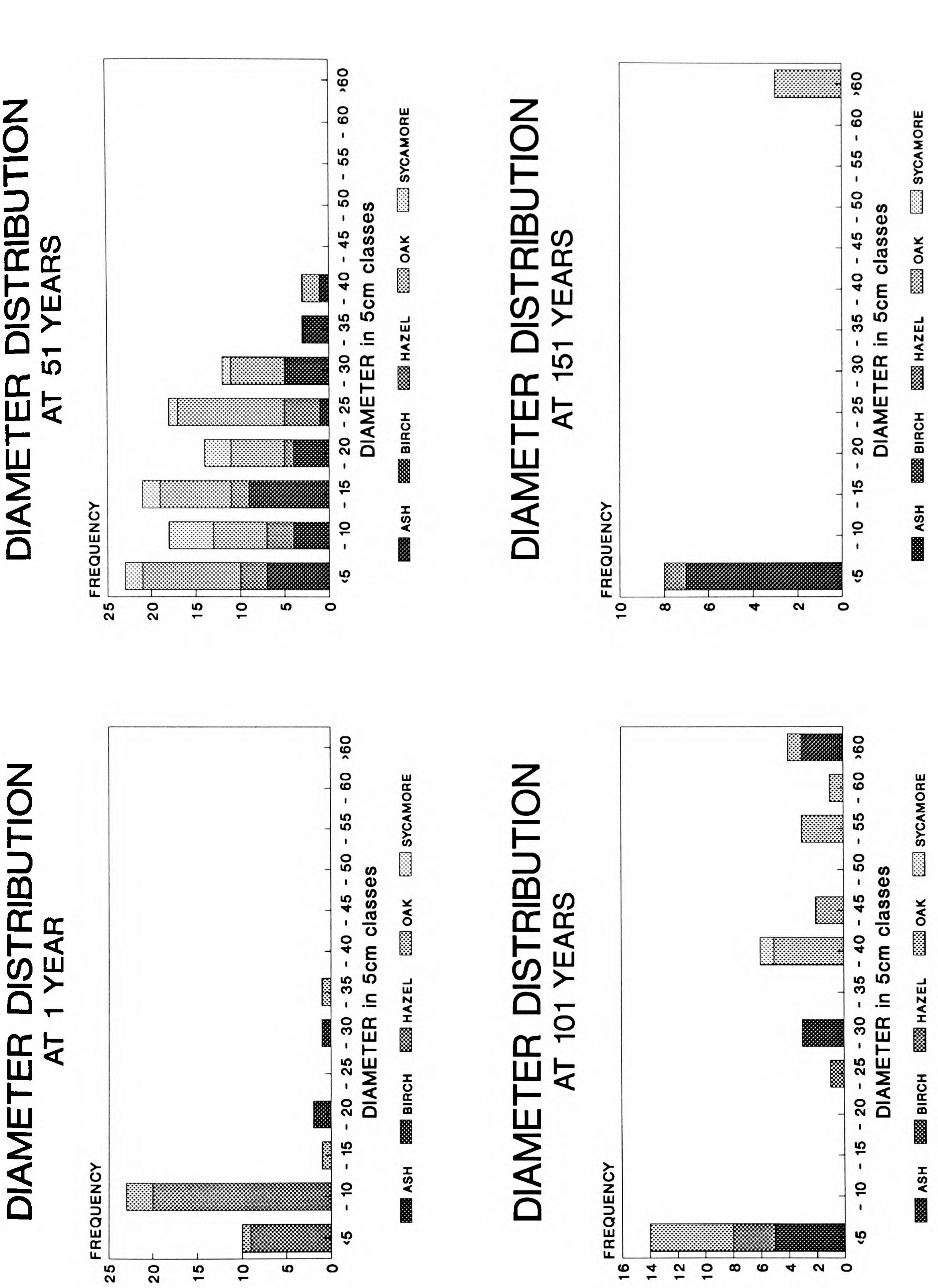


Figure 4.15a. Diameter frequency distributions at 50 year intervals from a single simulation of the '1967 stand' version of FORET for a 1/12 ha plot. Years 1, 51, 101, 151.

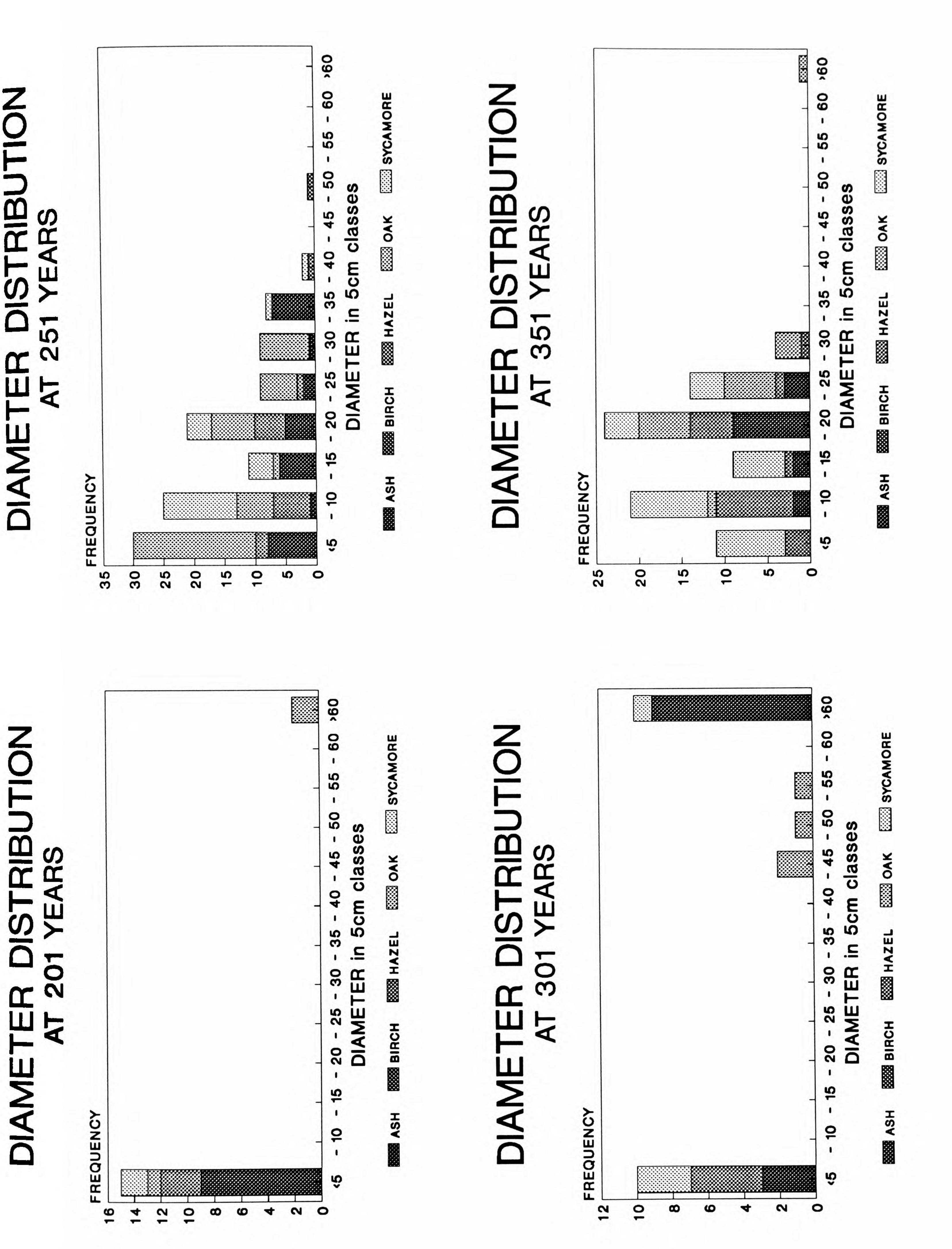
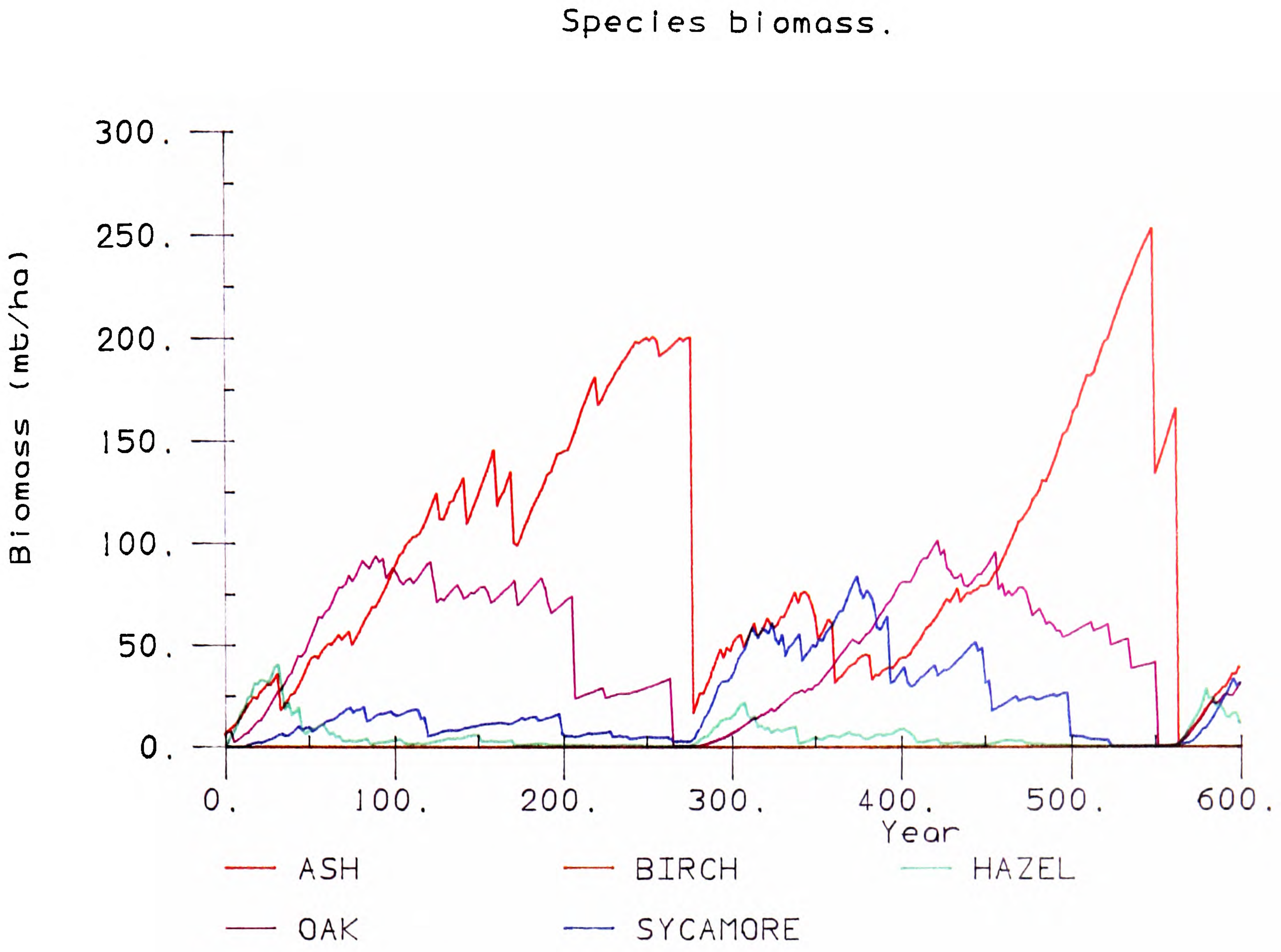


Figure 4.15b. Diameter frequency distributions at 50 year intervals from a single simulation of the '1967 stand' version of FORET for a 1/12 ha plot. Years 201, 251, 301, 351.


Species biomass.

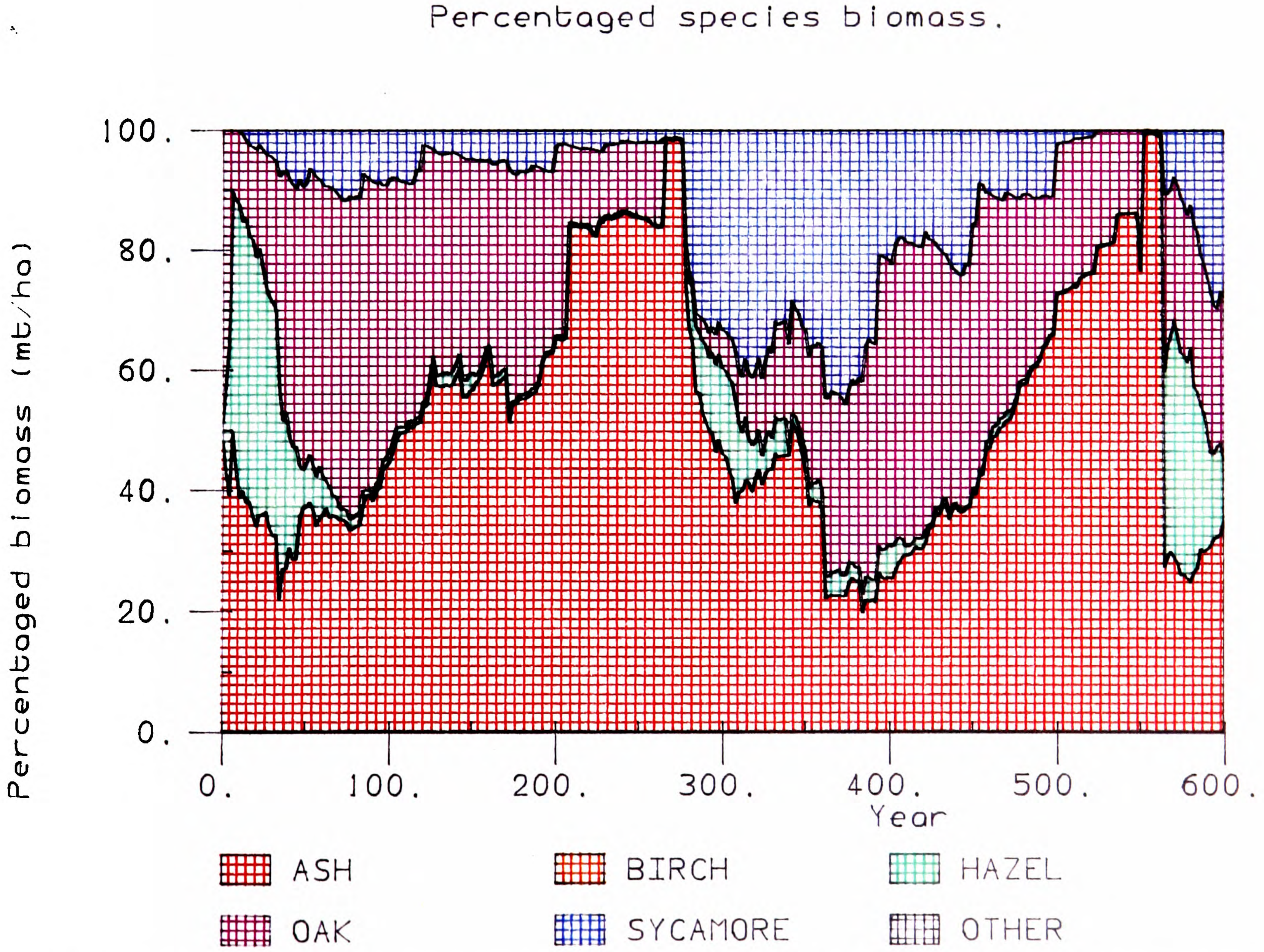

Percentaged species biomass.

Figure 4.16. Biomass plots from the '1967 stand' version of FORET for a single simulation of a modelled 1/12 ha plot. Biomass, however, is expressed per hectare.

number of small stems, the remaining two oaks have died by the year 251 and there has been regeneration and growth in the smaller stems. A similar cyclical pattern can be seen in plots of biomass by species for a single 1/12 ha plot (Figure 4.16). Clearly the model is reproducing the known phenomena of gap-phase replacement, or dynamic change in species and biomass composition over time.

4.12 Implications of errors in construction, and on predictions made by the model.

There are several broad categories of error that occur during the construction and use of complex computer models.

Firstly, many computations involving components, statistical analyses or preliminary simulations produce unbelievable results that defy a rational interpretation. They could, for example, be due to errors in data collection, incorrect modelling assumptions, or spurious programming syntax. Jeffers (1978) comments "[a] fact, not appreciated by many people not engaged in scientific research, [is] that nine out of ten research computations are 'wasted' in the sense that the computations are not used in the final results." These 'wasted' computations, are essential in gaining an understanding of the problem and its likely solution.

A second category of error is implicit in models that use 'general trends' to represent reality. In the construction of any dynamic 'ecosystem' model, many relationships are described by mathematical equations produced by statistical methods. For example, the variability shown in a scatterplot of diameter against height, or a diameter increment curve is represented, for convenience, by a single line. It is true that measures of dispersion of residuals about the 'least squares' lines can be estimated, but the magnitude of the possible errors must be considered in the context of the 'sensitivity' of the model. This is particularly important where a 'sensitive' factor, such as a growth equation, is involved in many 'feedback' relationships (Figure 4.17).

The new methodology for constructing growth equations was adopted in an attempt to reduce the magnitude of errors in the predicted output.

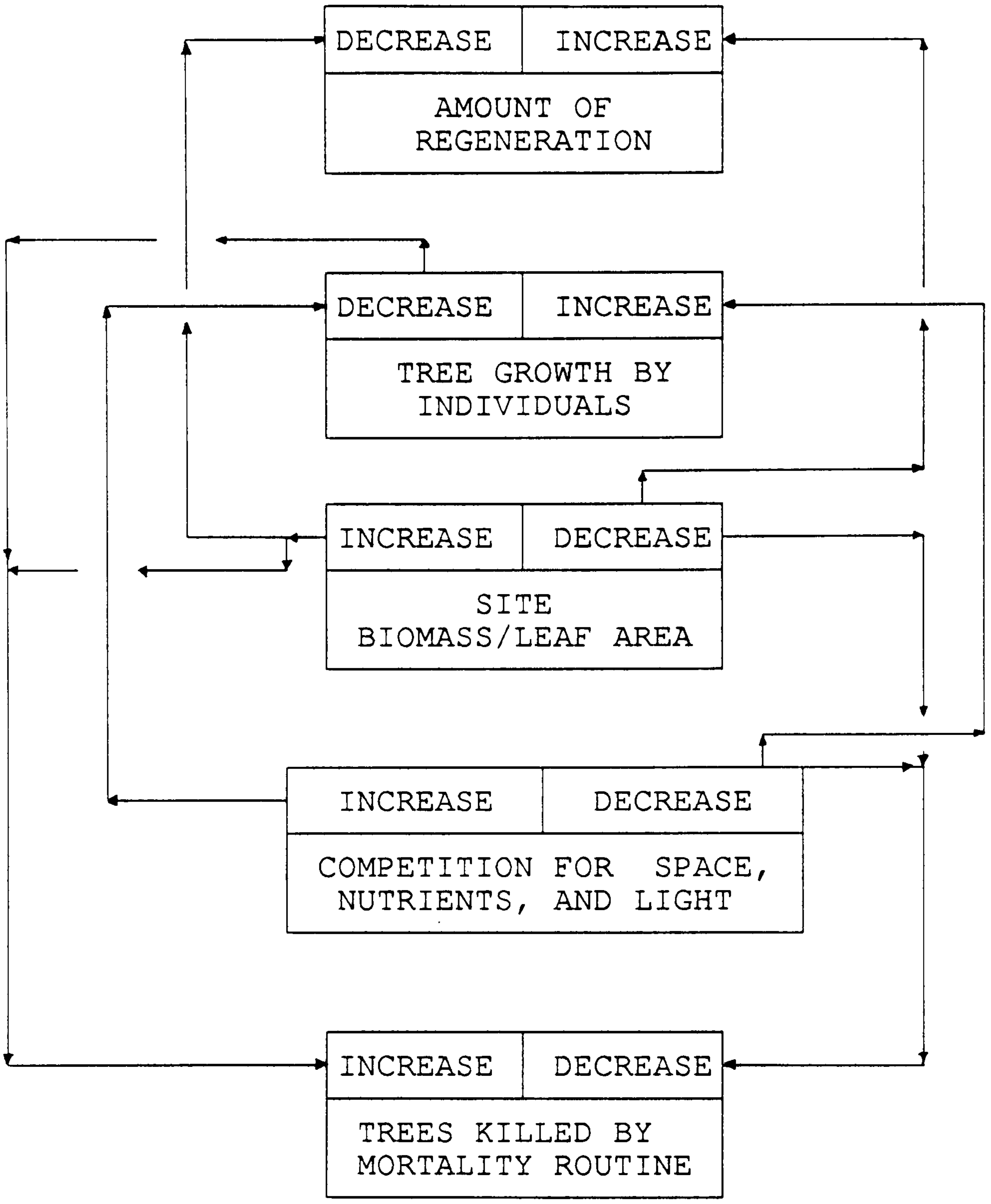


Figure 4.17. A flow diagram to represent the major 'feedback' loops between the processes of regeneration, growth, and mortality within the FORET model.

The likely effect of the variability in the height-diameter relationship is not compounded by its use in the new growth equation, because this too has been fitted by regression. If the general shape of the diameter increment curves is not greatly altered by different values for height-diameter coefficients, then it is likely that the method of fitting the growth equation to diameter increment data does not compound any inaccuracy produced by the use of height-diameter equations. This is true since the variability in the height-diameter relationships *between* species is most often greater than that *within* species, and similarly shaped diameter increment curves are produced for all species. At least, in this new methodology, any inaccuracy resulting from the use of a general growth 'trend' is limited to that inherent in the variability of the diameter increment data.

The same cannot be said for the original published method of growth curve construction. It is not possible to assess any variability in a species height-diameter relationship derived from measurement of a single tree. Assuming that American trees show variability in height for a given diameter, the assumptions concerning tree growth (via growth equations) will not tend to reduce the effect of any difference between the assumed relationship and those found in woodland to be simulated.

A third class of error results through the use of predicted estimates without any knowledge of the assumptions on which the model output is based. This must be a very common source of error as few people will bother to examine the detailed structure and components of a model when the output seems 'reasonable' and the model is very complex. This has already been seen, to a great degree, during the course of this research. Many workers have built on the original JABOWA model, whilst few have considered the validity of its fundamental components and assumptions. Predictions resulting from such work should be regarded with extreme caution. For example, in the current version of FORET for U.K. conditions, estimates of biomass are to be regarded with suspicion, as it is likely that biomass of large individuals is being predicted from a relationship that was derived for trees between an unspecified, but probably a fairly limited, range of diameters. Flewelling and Pienaar (1981) state that; for growth and biomass functions where estimates are based on multiplicative relationships, lognormal error distributions are produced.

The predictions made by the individual tree models in this research do not present any estimates for their variance. These would be useful for several purposes; (i) to gauge the reliability and precision of the values for predicted variables, (ii) to calculate confidence intervals, and (iii) to statistically test hypotheses when experiments are carried out on the models.

Gertner (1987) points out that for individual tree models with many component functions and analytical calculations, the direct prediction of variances for simulation results is almost impossible. This is due to the large numbers of interwoven functions, species specific parameter estimates, feedback relationships, and the iterative structure of the models.

There have, however, been several proposed methods of producing variance estimates for stochastic simulation models. For example, Gertner *op. cit.* suggest an error propagation method that assumes that errors are random in the input variables. Gertner and Dzialowy (1984) present a Monte Carlo method but this requires far greater computational power. Reynolds *et al.* (1981) stress the importance of an independent data set in the consideration of errors in a validation methodology, they suggest several statistical tests, both parametric and non-parametric, that may be of use in establishing the levels of accuracy for model predictions. Reynolds and Chung (1986) propose a regression methodology as an alternative to statistical testing. Errors from predictions are estimated as a function of the input variables of the model. Paradoxically, this is an example of a validation methodology for tree models that, itself, requires validation.

The models for U.K. conditions have yet to reach a stage of development where rigorous and complex validation methodology for predictions is useful. All derivatives of JABOWA that fail to predict reliably something as fundamental as diameter frequency distributions will also benefit from intensive verification. However, when the behaviour of the model has been rigorously verified, these procedures should be considered. Intensive verification should take precedence over complex validation of model predictions in the first instance. However, validation procedures for components of models should be attempted wherever possible.

4.13 Concluding remarks.

This Chapter has attempted to describe the development of a gap-model for U.K. woodland conditions. Several general improvements have been made. Species growth has been calibrated to diameter increment data and estimates for height prediction derived from analysis of a large survey of trees. Competition has been represented by a new multiplier, with a consequent improvement in the predicted diameter frequency distributions. The prediction of biomass for a given quality of site has been modified such that it is controlled by measures of density dependence and biomass increment, via mortality.

Finally, the improved versions of the model were tested against the known change in diameter frequency distribution for Meathop Wood in Cumbria. The results from predicted simulations were encouragingly similar. The difference between field measurement and the predicted output appears to be associated with the assumptions regarding the regeneration of trees.

The theoretical implications of single and multiple simulations, and sources of error within, and produced by, such models have been discussed.

CHAPTER 5. Summary and recommendations for PART 1.

This Chapter highlights the most important aspects, and discuss the implications of the research presented in Chapters 1 - 4. It concludes with recommendations for continued research activity in this subject.

5.1 A brief rationale for the subjects of research.

Since the introduction of grant schemes to aid the planting of broadleaved species there has been an increase in the rate of planting (Miller *et al.* 1988a and b). In addition there is a large amount of mixed broadleaved woodland in the U.K. that is neglected, or poorly managed, and produces timber at a lower rate than would be possible under management. Incentives for planting on agricultural land have been drastically increased under the Farm Woodland and Set-Aside Schemes. However, little is known about the growth of broadleaves, especially in mixed stands of uneven age.

There is a deficit in the understanding of the ecology of such woodland and an ever increasing need to be able to provide answers to the problems of potential management.

5.2 Selection of a suitable approach for research activity.

There are no long-established trials for even or uneven-aged, mixed deciduous woodland management in the U.K. Therefore, for the foreseeable future, some alternative method of study other than recurrent observation has to be attempted.

The logical approach is to develop the use of computer models. A suitable model will encompass the current state of knowledge and apply current ecological theories and hypotheses. If a model can reproduce known phenomena observed in woodlands, then its potential to predict the outcomes in unknown circumstances may be of use.

After consideration of the large number of published forest models available, and a discussion of the current ideas and theories in forest ecology a suitable modelling approach was identified. This approach describes forest development by simulating the growth and competitive interactions of each individual tree. Spatial relationships between trees are not specifically defined, this is a simplification of reality, but eliminates the requirement for specific spatial tree data to develop and test models. Spatial data are not available, and would restrict the application of forest models that make use of it.

A modelling approach previously used to investigate succession for various forest types was selected from the published literature. However, several major aspects of the existing models both in terms of the theories adopted, the methodologies used, and the performance produced, were found to be unsatisfactory. These can be summarised as;

i The central core of the models, the growth equations, was based on arbitrary assumptions concerning the pattern of growth of trees.

ii The rate of growth and the height-diameter relationship for an entire species was based on the maximum recorded dimensions of a *single* tree.

iii The use of the existing published methodologies for calibrating the existing growth equations produced unsatisfactory predictions when compared to the measured growth patterns of trees in the U.K.

iv The theoretical treatment and expression of competitive interactions and geographical species limits were inadequately expressed within the models.

v Competition for light was also based on the unsatisfactorily derived height-diameter relationships.

vi The output from selected models in terms of diameter frequency distributions were unrealistic.

vii The plot size of the selected model required matching to the size of mature trees.

viii Tree mortality was not matched to site quality in a satisfactory manner.

5.3 Sequence of research, and the main findings.

The first and foremost objective was to obtain reliable growth equations to substitute into the model. In order to achieve this, and improvements in the way competition for light is expressed, data for establishing species specific height-diameter relationships were required. This involved extensive fieldwork in many different woodlands.

Many regression analyses were performed, one for each of the candidate height-diameter equations for each species was carried out on each set of data. The final work used combined sets of data for each species.

Generally, height-diameter equations of the form;

$$Log(H - 130) = a + bLogD + c(LogD^2)$$

were found to be the most suitable for the species considered.

These studies showed that although there can be many possible heights for any given diameter of a species, the trends are quite clear. Oak was found to be unusual in that there is marked difference in the height-diameter relationship, which appears to depend on the conditions prevailing, in terms of spacing, during its development. Therefore, oak was given two height diameter curves that correspond to two broadly defined management treatments, 'high forest' and 'standards' oak.

Once the most suitable height-diameter equations had been identified, new forms of the growth function could be established by substitution. The resulting growth equations were calibrated by the adoption of a new methodology. Growth curve predictions were empirically matched to diameter increment data collected from widely spaced trees on fertile sites, thought to have developed largely in the absence of competition. Two parameters were varied in order to produce an acceptable fit to the observed data, these were the growth rate constant 'G' and the exponent of the diameter to leaf area relationship. The new growth equations were further matched to the diameter increment data by using the empirically derived values for these parameters as starting values in nonlinear regression analysis.

The results of this method of deriving growth equations was then compared to the published methodology. The two approaches showed a marked difference between basal area increment predictions for all the species considered. The published methodology did not produce predictions that corresponded to the patterns shown from field measurement. It is strongly recommended that the new methodology be adopted for calibration of growth equations in gap-models for any environment where diameter increment data are readily available (this may not be the case in the tropics).

The next logical step was to make use of the growth equations by substituting them into existing gap-models that had, to some extent, been modified for U.K. conditions. The performance of the modified models was assessed and aspects for further improvement were identified by making many investigative simulations. The underlying philosophy of improving the results produced by the model involved alteration of the expressions for regeneration, growth and mortality. This involved changes to many parameters, often simultaneously, producing three major improvements.

Firstly, the modelled growth was successfully improved by altering growth equations and growth multipliers. This involved the production of a new multiplier to express competition for space and limiting resources. The resulting diameter frequency distribution produced by the model became far more realistic.

Secondly, the modelled plot size was altered from 1/100 ha to 1/12 ha, this was necessary to allow large trees to approach their maximum size if they retain competitive dominance.

Thirdly, the magnitude of biomass predictions made by the model was altered so that site limitations were manifested via mortality to individuals, rather than a global reduction of growth rate.

There are two main limitations that have been experienced in this research that, at present, restrict the further development of these models. These are a lack of understanding of the ecology of regeneration and, most importantly, a lack of recurrent data from suitable sites against which the predictions made by the model can be tested further.

5.4 Suggested topics for further research.

Advances have been made, but more research, development and testing are required before the model can be used reliably for the prediction of management scenarios. However, this objective, although not fulfilled in this research, could be realised in the near future. The approach adopted in this thesis has the potential to achieve this aim.

Several aspects of ecology and modelling will require investigation;

i The study of regeneration has already been highlighted as one of the basic areas of research that requires greater understanding.

ii Developing the model to include representations of management interventions,for example, planting density for each species, thinning and felling at specified times or diameters.

iii Inclusion of individual tree volume and biomass partitioning functions Corbyn *et al.* (1988). The distribution of biomass within a stand is of particular importance to forest managers.

iv Testing model predictions against even-aged plantation data over normal rotation lengths.

v Development of other gap-models such as FORTNITE to allow comparison of similar modelling approaches.

vi Development of a growth *modifier* to represent annual climatic variation.

vii To link gap models that can predict the consequences of management interventions to methods of financial appraisal.

Of these recommendations only vi and vii require further discussion.

vi Growth trends have been represented by a single growth curve for each species fitted by regression, clearly some years produce far more growth than represented by the curves, and some years far less. This is often attributed to climatic variation, and it would be possible to include this variation by devising a multiplier that corresponds to the maximum deviation (positive or negative) for diameter increment. This could be represented in the form of a growth modifier that would effectively add or subtract diameter increment to each individual. The use of this modifier could be based on assumptions of stable climate by use of past meteorological data, or on the possible influence of climate change, eg 'global warming'.

vii Finally, another ideal objective for resource managers would be to link the flexibility offered by the modelling approach adopted in this study to a financial assessments. In this way the effects of altering the interventions in an ecological system could be directly reflected in the financial implications. At present this objective remains unfulfilled and indeed is often treated as being quite distinct from ecological research. It is, however, undeniable that the ecology and the economics of woodlands are fundamentally linked the moment management interventions in a 'natural' system are considered. Because gap-models in the U.K., or elsewhere, are not at a sufficient stage of development to be linked with economic studies, the economic analyses have formed a separate study in this thesis and will be described in Part 2.

PART 2.

CHAPTER 6. Economic studies on woodland management options.

6 Introduction.

This chapter extends previous work carried out by Crockford *et al.* (1987b) on the relative profitability of a wide range of woodland management systems. The updated study has been made in the light of policy changes regarding taxation, planting grants and the introduction of grant schemes available for trees planted on agricultural land (Spilsbury and Crockford 1989). The primary objective of the study was to produce a 'user friendly' computer program to guide potential forestry investors when selecting an appropriate forest management option under a range of financial circumstances. The resulting model allows the rapid comparison of investments and can highlight the sensitivity of the analyses to varying levels of the financial factors considered.

6.1 Previous work.

The initial study, carried out in 1986, considered the economics of eighteen management systems ranging from pure conifers, through mixtures of conifers and broadleaves to pure broadleaves in plantation, natural regeneration, and coppice systems Crockford *et al.* (1987a and 1987b). The analyses used the concept of Land Expectation Values (LEV's), to convert Net Discounted Revenues onto an infinite time horizon for each management option and each combination of variables, in order to facilitate comparison of the relative profitability of options with differing rotation lengths (this is described in greater detail in section 6.3.4).

6.2 The major variables.

A number of variables representing the most important factors affecting the profitability of woodland management in the private sector were considered. These included;

(i) choice of species and management system,

(ii) site quality and climate, reflected by a choice of yield classes for the species considered,

(iii) price combinations for fuel and timber based on national price surveys,

(iv) income tax rate, for the purpose of the schedule D to schedule B switch (which is due to be fully discontinued in 1993),

(v) grants from the Forestry Grant Scheme (FGS) or Broadleaved Woodland Grant Scheme (BWGS) for planting and natural regeneration,

(vi) management costs and sporting rentals (if appropriate)

and

(vii) discount rate at a choice of rates (0, 2, 3, 4 or 5 per cent).

6.2.1 Management assumptions.

Each management option has a set of predetermined management assumptions. These include the forest management operations carried out, their timings (which may depend on growth rate) and the costs associated with preparation and maintenance. For further details see Crockford *et al.* (1987b). The choice of management system can be influenced by many factors. The desired objectives of managing woodlands will be of considerable influence. The methods and analyses used in this chapter assume that the financial viability of an option will influence the final selection, regardless of any other criteria that may have been applied to the initial selection (the potential amenity and conservation value, for example).

6.2.2 Growth rates.

The choice of yield classes available are shown in the Table 6.1. They are based on national averages and ranges of yield classes (from Nicholls 1981) and represent low medium and high values for the species. Yield Class influences the timings assumed for the various forest management operations, including the overall rotation length.

Table 6.1 Yield classes of species for the management options considered.

MANAGEMENT OPTION.	Yield classes.		
	High	Med	Low
Plant with Douglas fir	10	14	18
Plant with Corsican pine	8	12	16
Plant with Japanese larch	6	10	14
Plant with Sitka spruce	8	12	18
Plant with Douglas fir/oak mixture	10/4	14/5	18/6
Plant with oak	4	5	6
Plant with Corsican pine/beech mixture	8/4	12/6	16/8
Plant with beech	4	6	8
Plant with oak/ash/cherry	4/4/7	5/6/8	6/8/9
30 year conversion to oak/ash/cherry	4/4/7	5/6/8	6/8/9
Underplant neglected woodland with western red cedar	12	14	18
Convert neglected coppice to coppice with standards	3	5	7
Re-coppice neglected oak coppice (normalised age)	2.5	4.5	6
Re-coppice neglected oak coppice (immediate conversion)	2.5	4.5	6
Plant simple coppice	3	5.5	8
Re-coppice neglected woodland of pure or mixed species.	3	5.5	8
Convert neglected woodland to an oak/ash group system	4/4	5/6	6/8
Shelterwood system for ash/sycamore	4	6	8
Beech natural regeneration	4	6	8
Birch natural regeneration	4	6	8

6.2.3 Prices.

The prices a woodland owner can expect for the harvested yield depends upon the stage of growth (size), the species and the market into which produce is sold. The revenue from the sale of produce is the remaining value after the costs of felling, and extraction are deducted from the selling price of the timber or fuel-wood. The price/size curves used in the study are high, medium and low values expected for the sale of standing timber. Several sets of curves were used, for conifers (grouped), other broadleaves (individually) and for fuel-wood. The timber produced from a management option is assumed to be sold into the most appropriate fuel-wood or timber market to maximise possible revenues, volumes being calculated from Forestry Commission management tables (Edwards and Christie 1981) and Crockford *et al.* (1987b). Five price combinations for fuel-wood and timber were considered in the analyses.

6.2.4 Discounting techniques and discount rates.

The method of calculation used for the economic analyses is based on standard discounting techniques described in detail in Pryor (1982) and summarised briefly below. To quote Pryor (*op. cit.*.) "The discounting procedure is simply a way of expressing and measuring the disadvantage of having to wait for a sum of money promised in the future, rather than having it now. Conversely, when applied to costs it expresses the advantage of being able to defer paying a cost until some date in the future, rather than paying it now". A future value is converted to a present value by multiplication with a discounting factor. The discounting factors are produced by application of the formula:-

$$\text{Discounting factor} = \frac{1}{(1 + i)^n}$$

Where 'i' = the discount rate per cent, and n = the years since management began.

Discounting factors are generated for the various discount rates by the application of this relationship. For example the discounting factor for the 3 per cent discount rate at year 5 would be $1/(1.03)^5 = 0.86261$. This, when multiplied by a cost or revenue occurring in year 5, gives the present value of that figure. Therefore any cost or revenue arising as a result of forestry management practices at any time from the start of management onwards into the future, can be expressed as a present value. The sum of the discounted costs and revenues is known as the Net Discounted Revenue (NDR), and can be calculated for different discount rates (not only integer values). The discount rate at which an NDR is exactly equal to zero is known as the Internal Rate of Return (IRR) for the management system. It represents the real return on the invested capital over the length of the management rotation.

The choice of discount rate greatly affects the magnitude of future costs or revenues in terms of their present values. Different discount rates are used to test financial viability at different real rates of return. The marginal opportunity cost of capital is reflected in the selection of an appropriate discount rate. No particular significance should be attached to the choice of discount rates, Five per cent is often used because it is the required rate of return for the nationalised industries, and three per cent is used by the Forestry Commission in land acquisition decisions.

6.2.4.1 Land Expectation Values (LEVs).

Different management options often have different rotation lengths, and since the technique of discounting is a method of expressing time-preference, direct comparison of the NDRs is not legitimate. To overcome this problem one must compare an infinite series of NDRs for a particular management option, in order that different options theoretically 'occupy' the land for the same length of time. This concept was first introduced by Faustmann in 1849 (*translated in* Linnard and Gane 1969) and the modified NDRs are known as Land Expectation Values (LEVs). There is a simple mathematical formula to convert NDRs to LEVs using the same notation as above;

$$\frac{\mathrm{NDR}.(1 + i)^n}{(1 + i)^n - 1} = \mathrm{LEV}$$

It should be noted that if a discount rate of zero per cent is chosen (i.e. time-preference is eliminated) then the LEV is theoretically of infinite value. The analyses in the computer model present undiscounted net benefits (or losses) for one rotation only for zero per cent analyses.

6.2.4.2 Benefit-Cost Ratios (BCRs).

BCRs are calculated by division of the *gross* LEV by discounted costs in perpetuity. Price (1989) comments: "Investments are acceptable if the benefit-cost ratio exceeds unity. This always gives the same result as accepting investments whose NPV [net present value] is positive". The BCR is a measure of the efficiency of an investment, it is the NPV per pound invested. The change from a BCR with a value greater than one to a value less than one is called the 'switching point'.

6.2.4.3 Forest rent.

Forest rent is calculated from the division of net undiscounted benefits (or costs) by the rotation length; it is, therefore, the average annual net revenue. An investment is acceptable if the value of forest rent is positive when comparing investments the one with a larger value is selected. Traditionally, this measure of profitability has been applied to forests where a near-normal age distribution exists, particularly in Germany and France. It is argued that discounting is inappropriate for systems that must remain forested by law and yield a constant volume of timber per annum which is continually replanted. No consideration is made of the timing of costs and revenues.

6.2.5 Grants and Taxation.

The influence of taxation and grants available to potential investors in woodland management systems was also included in the analyses, and the initial studies (pre-1988 Budget) considered the availability of tax relief under Schedule D with a tax switch to Schedule B before the production of first revenues, where appropriate. The effect of remaining on tax schedule B, without a tax switch, was also examined. Grants were considered under the schemes in operation at the time, namely the BWGS and FGS (Forestry Commission 1987, 1985a).

Table 6.2 Summary of regulations for taxation schedules D and B adapted from Hart (1979) and Forestry Commission (1985b).

Schedule D Assessments	Schedule B Assessments
Losses from the establishment or management of woodland can be offset against taxable income. Profit made under schedule D is eligible for taxation. Changing ownership automatically reverts the woodland to taxation under schedule B.	Annual payment of one third of 'prairie' value of land. Valued commonly at £1 per hectare. Tax payable does not vary with revenues, losses or grants paid. Losses *cannot* be offset against taxable income.

Applications for registration to tax schedule D for forestry purposes closed immediately after the presentation of the 1988 Budget. Tax relief for forestry investors with existing investments registered for schedule D assessment will continue until the end of the financial year in 1993.

6.3 Computer program for the study of financial scenarios.

In order to generate and compare the large number of possible financial evaluations without having to consult complex tables or perform laborious calculations, a computer program was produced by Spilsbury (1987). This is a flexible system for the rapid examination of economic analyses including the full range of management options and variables. The original program was developed using data from the studies of Crockford (1987) and Dolan and Russell (1985). Construction of the program was greatly influenced by the desire to produce an end result that was as 'user-friendly' as possible, and compatible with a large number of microcomputers. The aim of this portability was to enable the use of the program by forestry consultants and advisors in the hope that it would guide land owners deciding to invest in forestry. The LEVs produced by the program can be used to compare the relative profitability of woodland management options under varying economic conditions.

6.3.1 Financial modelling and systems analysis.

The systems analysis framework was applied during the development and testing of the computer model (see foreword). *Recognition of the problem*; No suitable models/computer programs that allow rapid comparison of long-term profitability for a range of forest management options exist. *Definition and bounding of problems*; economic comparisons were to be investigated for a variety of forest management systems, and the analyses were simplified by consideration of only the most important variables. *The goals and objectives were*; to model accurately the profitability of forestry investments, whilst retaining the emphasis on ease of use and portability of the model to many computers. An algorithm was developed for *generation of solutions* consisting of a central program designed to access different data sets for different management options. The structure of the model is shown in Figure 6.1.

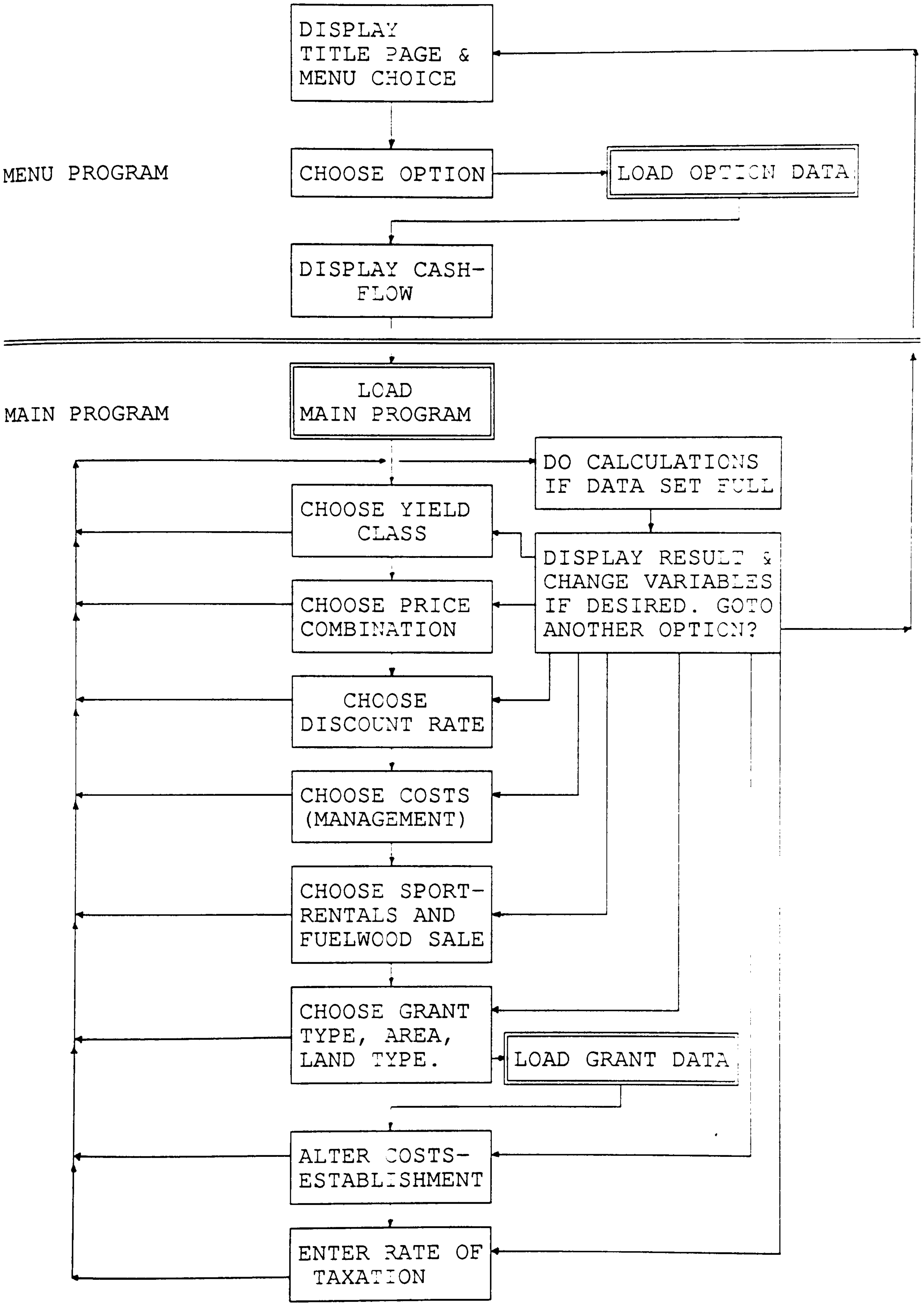


Figure 6.1. Flow diagram for the economics program WOODMAN III.

The final model was then used for research, teaching and advisory purposes, however, the 1988 budget brought changes that necessitated modification of the model, and reiteration through the systems analysis framework.

Software was developed in GWBASIC for IBM or compatible machines (Listing in Appendix 3). All the data required by the program are contained in a large number of random access files, stored on a computer disk with the program files. Each management option has a series of associated data files. The program reads the fundamental data for LEVs of different price and productivity combinations at a specific discount rate. These are then modified by a series of additional discounted costs or revenues that are pre-multiplied by the appropriate LEV multipliers.

6.3.2 Verification and validation.

The verification of the analyses considered in the model was a simple matter of repeating the analyses by manual calculation and by reference to tabulated analyses, based on identical data, presented by Crockford *et al.* (1987b). Validation of the model was more empirical, in that it relied on the similarity to the findings of other authors working on the profitability of similar management systems. The output from the model concurred well with studies by Pryor (1982), and Lorrain-Smith (1982 and 1988). Verification procedures were repeated with successive versions of the model and validation, post 1988-budget, was possible with the studies of Leslie (1989).

6.4 Comparison of new and old programs - the 1988 Budget.

The results of comparisons of many different economic circumstances, generated by using the program, indicated the intrinsic profitability of different woodland management systems. They demonstrated that for the majority, tax relief on expenditure was a major factor in increasing the profitability at any discount rate. Grants (BWGS/FGS) at that time, however, were only sufficient to offset some of the costs of establishment and did little to bridge the income gap between investment of capital and the realisation of a return. This was notably conspicuous for the capital-intensive plantation options (Crockford *et al.* 1987b).

With the announcement in 1988 of the Woodland Grant Scheme (WGS), to replace the FGS and BWGS, the Farm Woodland Scheme (FWS), the Set-Aside Scheme (SAS) and the Chancellor removing tax incentives for forestry, woodland economics in the private sector have considerably altered. The updated study attempts to highlight the importance of these changes on profitability both within and between management options. This was accomplished by comparing results from the previous computer program, based on pre-budget financial circumstances, with a new updated program (Spilsbury 1987, 1988) designed to include all of the possible grants and subsidies available for private forestry at present. To avoid repetition of the survey of costs carried out in 1985/1986 (Dolan and Russell 1985), all the costs and prices used in the initial study were inflated to May 1988 values for use in the new computer program. The new program was of almost identical format but included new programming routines to cope with the greater variety of grants available,their conditions of eligibility and changes in tax legislation.

6.4.1 The effect of taxation - equilibration of financial scenarios.

The results show how the profitabilities of woodland management have changed, not only for those able to take advantage of the new incentives offered for the planting of agricultural land, but perhaps more significantly for those concerned with the management of woodlands not eligible for the Farm Woodland or Set-Aside Schemes (Spilsbury 1989).

The effect of the removal of tax incentives on profitability was investigated by comparison of identical scenarios representing the long-term profitabilities both before and after the budget. *The levels of income tax relief on expenditure were varied in the pre-budget model until LEVs equalled the post-budget values.* This gives a measure of the extent to which a management option was dependent upon income tax relief to increase profitability with respect to the post-budget circumstances. These comparisons were made only for options in which the schedule D to B tax switch was possible, and financially advisable.

Table 6.3 shows the level of income tax at which the pre-budget (D/B switch) and post-budget (no tax relief) LEVs equate. The financial comparison was made at a three per cent discount rate, assuming average yield classes, medium prices for fuel-wood, timber and management costs.

Grants are at the lowest rate (over 10ha BWGS, FGS or WGS) and the sale of lop and top for fuel-wood is included for broadleaf and broadleaf/conifer options.

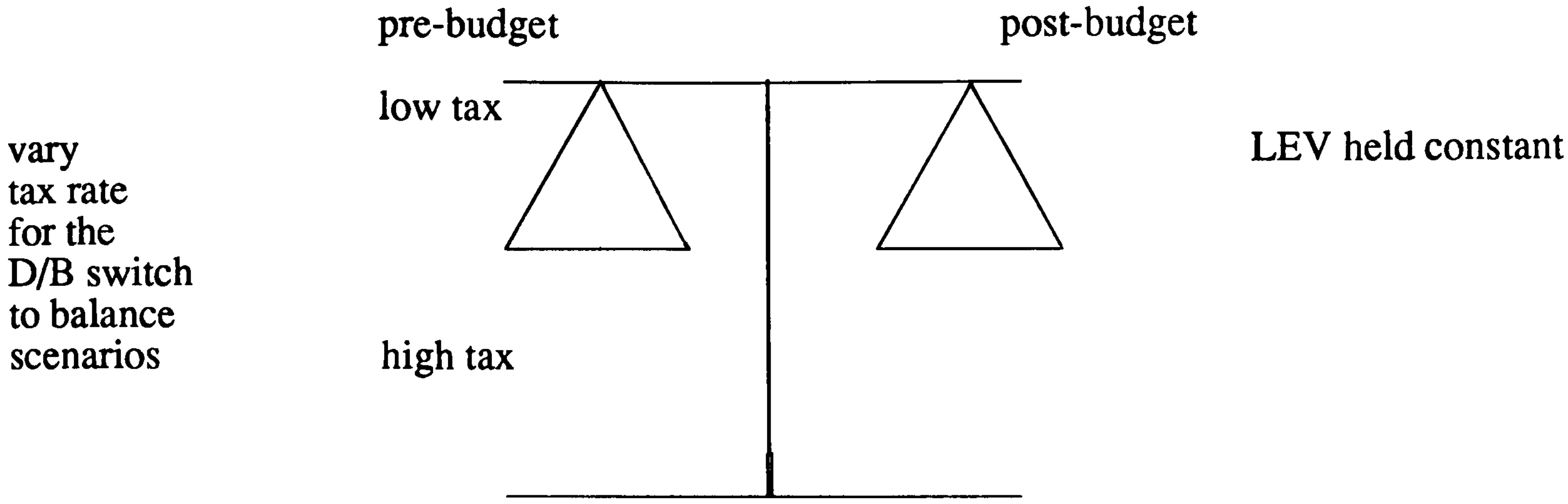


Figure 6.2. Diagrammatic representation of the method used to 'balance' economic scenarios, a larger LEV is considered 'heavier'.

Table 6.3. Levels of income tax relief that were required to match pre-budget LEVs to post-budget LEVs for a range of management options.

MANAGEMENT OPTION	Level of income tax relief required to match pre-budget LEV.
Douglas fir plantation	37
Corsican pine plantation	39
Japanese larch plantation	42
Sitka spruce plantation	40
Douglas fir / oak plantation	46
Oak plantation	32
Corsican pine / beech plantation	38
Beech plantation	25
Oak / ash / cherry plantation	36
Planting simple coppice	55

If a woodland owner was in receipt of tax relief for any of the management systems shown in Table 6.3 at a level greater than that required to match pre-budget with post-budget LEVs, the present circumstances of increased grants (WGS), but no tax relief indicates a reduction in the long-term profitability of the management system. For example, beech plantations show a reduced profitability for everyone (given the assumed yield class, prices, discount rate etc.) since the previous lowest tax rate was 30 per cent and the tax rate below which an increase in long-term profitability would be experienced, is 25 per cent. For low income earners, with correspondingly low tax rates, the present fiscal arrangements represent a net increase in the long-term profitability of these options if their previous rate of tax relief fell below the percentage 'balance' point for the management option. The 'balance' points in Table 6.3 are specific to the levels of the variables chosen. However, alterations to the variables considered cause predictable changes in LEVs and, consequently, alter the levels of tax relief required from the pre-budget system to match LEVs generated from the present fiscal arrangements.

Lowering yield class reduces the LEVs and therefore lowers the rate of tax relief required to match the present values. This is intuitively obvious since any factor acting to reduce profitability can be matched from the previous system with less dependence on tax relief on expenditure. Thus a low tax relief balance point means that a large range of woodland owners in tax brackets from the balance point upwards will be suffering a net loss in the long-term profitability of a management option (because tax relief is no longer available to enhance LEVs). Conversely, economic factors which act to increase LEVs (e.g. increased yield classes, higher prices, or lower discount rates) will produce a higher tax relief balance point when the pre-budget and post-budget profitabilities are compared. To illustrate this, Sitka spruce plantations at a three per cent discount rate, with medium yield class, medium price conditions, medium management costs, no sale of lop and top but planting grants at the highest rather than the lowest rate were compared. The result was a raised balance point from the 40 per cent shown in Table 6.3, to 56 per cent. For this situation, only those woodland owners who were in receipt of tax relief in excess of 56 per cent (before the budget) will be suffering a long-term decrease in the profitability of the option. All owners below this level will be enjoying an increase in the long-term profitability due in part to the greater levels of grant payable under the WGS. Another example, this time for oak plantations of yield class 6, in areas where the timber and fuel-wood markets provide high prices, and considering WGS grants at the lowest rate (over 10ha) the pre-budget to post-budget balance point rises from 32 per cent (shown in Table 6.3) to 45 per cent, thereby showing an increase in the long-term profitability for woodland owners in the lower tax brackets (always remembering those in higher tax brackets now find the option less economically attractive).

The results of many comparisons similar to the few illustrated above, indicated that the changes in long-term profitability of woodland management systems as a result of the changes in fiscal policy can be highly variable depending on the exact combination of the variables used to define particular economic circumstances. It became evident, however, that the scenarios least likely to suffer from the recent changes in fiscal policy are those with intrinsically high profitabilities resulting from high yield classes (shorter rotation lengths), good prices for fuel-wood / timber and high grant rates. These effects were not confined to the capital-intensive high productivity management systems but applied also to the low input forms of forestry, such as a shelterwood system for ash and sycamore or conversion of neglected woodland to an oak/ash group system. These management options which were less, if at all, dependent upon tax relief, due to the nature of the silvicultural practices, showed higher post-budget LEVs due to low establishment and maintenance costs and increased grants under the WGS.

6.4.2 Long term profitability and planting incentives.

So far this study has concentrated on the effect of the budget on owners unable to benefit from the enhanced rates of grant payment available for the establishment of woodland on agricultural land through the Farm Woodland and Set-Aside Schemes. It has been shown that the changes in long-term profitability of a wide range of management options due to the changes announced in the 1988 budget can be advantageous or detrimental, and that this is dependent on the intrinsic profitability of the management option and the levels of the other economic factors considered. Nevertheless it is recognised that the long-term profitability of woodland management systems is not the sole consideration in a decision to invest. The more immediate concern of a potential owner will be the length of time between the investment of capital and the generation of a return. Even if the long-term profitability of the proposed management option has increased, the withdrawal of tax relief makes any investment seem more immediate to the owner, since an investment can no longer be created out of money that would otherwise have been requisitioned by the Chancellor.

If we consider the tax relief balance point for an oak plantation of 32 per cent (shown in Table

6.3) it will be noted that there is a marginal increase in the long-term profitability of the option if the rate of tax relief available to an owner were below 32 per cent. However, reference to the data shown in Table 6.4 for oak plantation shows that the owner does not receive any returns until 35 years after planting, and a positive cumulative discounted revenue (at a three per cent) is not secured until clearfelling at year 120. It is obvious that the marginal increase in long-term profitability will not act as an incentive to promote new planting for the poorer woodland owners experiencing this combination of economic factors. It is the initial investment and prolonged management costs incurred before the generation of any thinning revenues that is likely to discourage planting of new woodlands not eligible for the FWS or SAS.

Table 6.4 Rotation lengths, year of first revenues (from the sale of wood products), and year in which the cumulative discounted revenue (at 3 per cent) becomes positive for the management options shown. Figures are generated from scenarios using the same parameters for yield class, fuel-wood and timber as used in Table 6.3.

Management option	Rotation length	Year of 1st revenues	Year cumulative discounted revenue is +ve
Douglas fir plantation	52	21	47
Corsican pine plantation	54	24	49
Japanese larch plantation	44	19	39
Sitka spruce plantation	55	25	50
Douglas fir / oak plantation	120	27	55
Oak plantation	120	35	120
Corsican pine/beech plantation	92	24	52
Beech plantation	95	35	95
Oak / ash / cherry plantation	120	30	60
Underplant western red cedar	64	28	32
Convert to coppice &standards	85	25	85
Planting simple coppice	28	28	28
Ash / sycamore shelterwood	76	30	10
Beech by natural regeneration	95	35	95
Birch by natural regeneration	50	25	50/0*

* cumulative discounted values are only positive at year 0 if grants are payable, otherwise values become positive at year 50.

6.4.3 Grants to replace agricultural income.

For farmers considering conversion of land, previously used for agricultural purposes, into new woodlands there are several options. The number of different courses of action that are available to any one landowner is dependent on previous crops grown, and the agricultural classification of the land. Table 6.5 summarises the possibilities and the conditions of eligibility with respect to land types.

The rates of payment associated with the different grant schemes depend on the type of land planted, species used, size of area and the previous crops grown on the land (if any). The choice of scheme will be influenced not only by the relative financial incentives provided, but also by the conditions of the schemes themselves. For example, those eligible for the Set-Aside scheme enter the scheme for five years but have the option to withdraw after three, the Farm Woodland Scheme, however, requires commitment of the land to forestry for longer periods of time, up to forty years.

Table 6.5 Eligibility for differing grant schemes with respect to land type, adapted from Timber Growers U.K. (1988).

Agricultural land	WGS only	WGS & BLS	FWS & WGS	FWS & SAS	WGS & SAS
Arable (approved crops)	YES	YES	YES	YES	YES
Arable (other crops)	YES	YES	YES	NO	NO
Improved grassland	YES	YES	YES	NO	NO
Unimproved grass in LFA	YES	NO	YES	NO	NO
Other agricultural land	YES	NO	NO	NO	NO

WGS = Woodland Grant Scheme, BLS = Better Land Supplement, FWS = Farm Woodland Scheme, SAS = Set-Aside Scheme.

The figures shown in Table 6.6 give LEVs for selected management options under the different combinations of grant types, land classification and income taxation. Cases where the tax rate is not specified indicate that it does not affect profitabilities under these grant schemes.

The magnitude of the effects on profitability of the various grant combinations available is best illustrated by comparison with the LEVs shown for 'no grants'. For the better land types, the FWS (with either WGS or SAS) enhances the LEVs by the greatest margin, but the SAS/WGS still gives a significant increase in profitability. Taxable payments within the FWS are determined by land type and species. Rates for land outside Less Favoured Areas are £190/ha/yr. Within LFAs there are two rates, £150/ha/yr in disadvantaged areas, and £100/ha/yr in severely

Table 6.6. Land expectation values are shown for the selected management options at a 3 per cent discount rate, with medium yield classes and medium values for fuel-wood and timber prices. The sale of lop and top for fuel-wood is included for the broadleaf and broadleaf/conifer options. Planting grants are included at the lowest (over 10 ha) level in all cases. Tax differences, where shown, relate to grant schemes providing taxable income (shown at present maximum and minimum rates 25 and 40 per cent).

Management. option	Agricultural land type.	No Grants	WGS only	WGS & BLS	WGS & FWS. 25%	WGS & FWS. 40%	FWS & SAS. 25%	FWS & SAS. 40%	WGS & SAS. 25%	WGS & SAS. 40%
Douglas fir plantation.	Arable (approved crops) not LFA	2283	3025	3225	5273	4733	5273	4733	3900	3725
	Improved Grassland in DA	2283	3025	3225	4705	4278	----	----	----	----
	Unimproved Grassland in SDA	2283	3025	----	2999	2914	----	----	----	----
Sitka spruce plantation.	Arable (approved crops) not LFA	1617	2342	2542	4539	4011	4539	4011	3197	3026
	Improved Grassland in DA	1617	2342	2542	3984	3567	----	----	----	----
	Unimproved Grassland in SDA	1617	2342	----	2317	2233	----	----	----	----
Douglas fir/oak plantation.	Arable (approved crops) not LFA	1190	1966	2166	4842	4266	4842	4266	2673	2532
	Improved Grassland in DA	1190	1966	2166	4236	3782	----	----	----	----
	Unimproved Grassland in SDA	1190	1966	----	2420	2329	----	----	----	----
Oak. plantation	Arable (approved crops) not LFA	-656	294	494	3685	3007	3685	3007	1001	860
	Improved Grassland in DA	-656	294	494	2971	2436	----	----	----	---
	Unimproved Grassland in SDA	-656	294	---	829	722	----	----	----	---
Beech plantation.	Arable (approved crops) not LFA-657		325	525	3830	3129	3830	3129	1056	910
	Improved Grassland in DA	-657	325	525	3093	2539	----	----	----	---
	Unimproved Grassland in SDA	-657	325	---	879	768	----	----	----	---
Oak/ash/cherry plantation.	Arable (approved crops) not LFA	14	965	1165	3840	3265	3840	3265	1672	1530
	Improved Grassland in DA	14	965	1165	3235	2781	----	----	----	----
	Unimproved Grassland in SDA	14	965	----	1419	1328	----	----	----	----

WGS = Woodland Grant Scheme, BLS = Better Land Supplement, FWS = Farm Woodland Scheme, SAS = Set-Aside Scheme, LFA = Less Favoured Area, DA = Disadvantaged area (within LFA), SDA = Severely Disadvantaged Area (within LFA), ---- = Grant not available for land type.

disadvantaged areas. Planting of oak or beech attracts payments for 40 years, other broadleaves for 30 years, conifer woodland planted with less than 50 per cent broadleaves for 20 years and traditional coppice for 10 years. The SAS/WGS has the full WGS planting grant rate and annual taxable payments for five years at £200/ha/yr outwith LFAs and £180/ha/yr within them. Although payments are quite high and a land owner is initially only committed to the scheme for three years. It is hard to envisage an owner planting land with trees, receiving payments for three years, then deciding to opt out of the SAS/WGS and consequently incurring the cost of the removal of the trees to enable an alternative land-use. There are provisions for other alternatives besides forestry within the SAS that would be less costly to abandon. It is more likely that an owner opting for planting trees will realise the long-term commitment required and favour higher profitabilities and extended annual payments available from the FWS/WGS or the FWS/SAS. The WGS and Better Land Supplement is an additional non-taxable payment of £200/ha at planting and as such only increases the LEV by £200 from the ordinary WGS payments. An owner qualifying for this payment should be eligible for the FWS/WGS and would be best advised to enter this scheme in preference.

The major problem for the owner is the initial cost of establishment and maintenance of a woodland. A series of annual payments is exactly the practical financial assistance required to promote more planting and better silvicultural care of a crop during its development. For this reason and, the relative influence on long-term economics, a one-off non-taxable BLS payment would be inadvisable.

For the lowest category of land that qualifies for FWS payments, namely unimproved grassland in Severely Disadvantaged Areas, the economic advantage may be marginal for conifers, and it can be more favourable to register for the WGS only. However, for broadleaves and broadleaf/conifer mixtures (maximum 50 per cent conifers) the FWS represents a significant increase in profitability when compared to values for the WGS only. The reason for this is that although annual FWS payments are considerably lower for this type of land (£30/ha/yr), they continue longer for the management of broadleaved species than for conifers which also receive planting grants at a lower rate under the FWS (payments equivalent to the old FGS) than those available for the WGS only. It appears that this policy will encourage increased planting of broadleaves, although broadleaf/conifer mixtures, if properly managed (and planted in correct proportion), can benefit from high grant levels and the earlier returns yielded by conifer species.

6.4.4 Conclusions with respect to present fiscal incentives.

It comes as no surprise that the long-term profitabilities of woodland management options have been greatly increased through schemes such as the FWS and SAS, and they should succeed in encouraging increased woodland establishment on agricultural land. Yet there are still many aspects of the new policy that are uncertain. Not least of these is whether the policy will help to reduce the production of agricultural surpluses. The introduction of similar set-aside schemes in the USA is an example of the unsuccessful application of such policies (Fennell 1988). Land owners will be concerned with individual micro-economic solvency and may tend to increase productivity on the remaining agricultural land in order to maintain, or enhance, individual revenues, thus the cumulative action of individuals will act to frustrate the aims of the policy. Another problem may be attainment of the target of 36,000 ha of new woodland planting per year set by the government. The provisions of the FWS, state that a maximum of 36,000 ha can be planted under this scheme over three years (presumably about 12,000 ha/year), but we have seen a reduction in the long-term profitabilities of woodland management options for many woodland owners (not eligible for FWS/SAS) especially in the higher tax brackets who represented the majority of investors, since the removal of tax relief on expenditure for forestry after the 1988 budget. It is, therefore, very likely that a net fall in the annual rate of planting will be seen, since any potential compensating effect of increased planting by those eligible for the new grant schemes has been restricted by the government limit set on such planting.

6.5 The economic prospects for 'natural' management in the U.K.

This study has been produced largely in response to a recently published paper (Leslie 1989) in which the financial/economic feasibility for the 'natural' management of forests was discussed and compared to 'standard' plantation forestry in temperate regions. The use of the computer model produced provides an opportunity to carry out an alternative study for the fiscal conditions prevailing in the U.K.

6.5.1 Measures of financial attractiveness.

The objective of this work is to demonstrate how the relative profitabilities (financial attractiveness) of forestry management systems are affected not only by the financial variables which are commonly considered but also by the method of analysis. The intention is to highlight comparisons between traditional plantation forestry and more 'natural' methods of management. It is left to the reader to compare the relevant scenarios in terms of the likely productivity of different species on a given site. The financial appraisals presented are entirely concerned with pre-investment long-term estimates of profitability as a basis for the selection of possible management options.

Relative profitabilities have been examined for a variety of forestry management regimes in the U.K., ranging from intensive coniferous plantations to broadleaved management systems relying on natural regeneration. The analyses are based on scenarios produced by the computer model. Estimates of financial performance are presented for management alternatives using three different criteria for the selection of forestry investments; net land expectation values (LEVs), the benefit-cost ratio (BCR) and the forest rent.

LEVs are calculated by converting net discounted revenues onto an infinite time period (see section 6.3.4.1), enabling management systems with different rotation lengths to be directly compared. For a full discussion refer to Pryor (1982). BCRs are calculated by division of the gross LEV by discounted costs in perpetuity. Price (1989) comments: "Investments are acceptable if the benefit-cost ratio exceeds unity. This always gives the same result as accepting investments whose NPV [net present value] is positive" (section 6.3.4.2). Forest rent is calculated from the division of net undiscounted benefits (or costs) by the rotation length; it is, therefore, the average annual net revenue. The *ranking* and therefore selection of potential investments may differ for each measure.

6.5.2 Ranking the 'naturalness' of management options.

The analyses cover the same set of variables considered in the model and used in the studies presented in section 6.3. Several management options are examined; they have been ranked from the least to the most 'natural' in character. The editor's footnote in Leslie (*op. cit.*) helps clarify exactly what is meant by this: "natural management can be taken generally to refer to forestry practices which may involve long rotations, low yields, slow growing native species, use of natural regeneration, etc". The ranking was formulated with this in mind, but also with consideration to the following: the type of trees involved (native and/or broadleaved versus exotic and/or coniferous), the intensity of management operations (potential site disturbance), and the potential species diversity (excluding the trees). Table 6.7 shows the categories of the management options used in the analyses.

Table 6.7. Ranking of management options with increasing level of 'natural' management and the associated range of yield classes for three productivity levels.

MANAGEMENT OPTION.	Yield class ranges		
	Low	Med	High
LESS 'NATURAL' (plantation)			
Plant with Sitka spruce	8	12	18
Plant with Douglas fir	10	14	18
Plant with Japanese larch	6	10	14
INTERMEDIATE			
Plant with Douglas fir/oak mixture	10/4	14/5	18/6
Plant with beech	4	6	8
Plant with oak	4	5	6
Plant with oak/ash/cherry	4/4/7	5/6/8	6/8/9
MORE 'NATURAL'			
Shelterwood system for ash/sycamore	4	6	8
Re-coppice neglected oak coppice	2.5	4.5	6
Neglected woodland to oak/ash group system	4/4	5/6	6/8
Beech natural regeneration	4	6	8
Birch natural regeneration	4	6	8

The detailed assumptions for each of the options used, including prices for timber and costing for operations are based on those used by Crockford *et al.* (1987b) but inflated to 1988 values.

6.5.3 Levels set for important variables.

In order to compare the relative profitabilities of each management option, similar values were selected for each of the variables considered across all the choices. For the purposes of the study grants were always taken to be at the lowest rates paid under the WGS (areas over 10ha), unless the assumptions for the management option implied a different size of planting area (e.g. group systems having smaller planting areas and therefore higher grants, and re-coppicing options not being eligible for grants). FWS and SAS payments were not considered in the scenarios, therefore removing the requirement to include income tax. For a discussion of the effect of planting incentives on different land types refer to Spilsbury and Crockford (1989). Revenues from sporting rentals were not included. Prices for fuel wood and timber were selected at the national average values from the price combinations available. Results were produced for each management option in terms of a BCR and a LEV or forest rent. Six tables are presented, two for each range of yield classes.

6.5.4 Comparison of financial scenarios.

The magnitudes of LEVs, BCRs or forest rent are often used as a basis for making decisions between alternative forestry investments. It is therefore instructive to compare the outcome when different selection measures are applied.

No specific site types have been defined and the reader should refer to Table 6.7 and determine the likely range of yield classes possible for a given site and particular management system. The financial viability for different systems can then be compared across productivity levels (if necessary) by careful reference to Tables 6.8-6.13. For example; a given site may support yield class 12 $m^3ha^{-1}year^{-1}$ (medium range) Sitka spruce but only yield class 4 $m^3ha^{-1}year^{-1}$ (low range) oak. Comparison of BCRs would require reference to Table 6.9 for oak and Table 6.11 for Sitka spruce.

6.5.5 Outcome of alternative financial analyses.

The results shown in Tables 6.8-6.13 show the expected trends but also highlight some interesting effects. The most obvious tendencies are that increasing productivity (yield class) acts to increase LEVs and BCRs, whilst increasing the discount rate results in a rapid reduction of these values. Forest rent increases directly with the level of productivity because discounting is not involved. This is true for all of the management systems.

In order to calculate a BCR there must be some net benefits, if net costs exceed net benefits then the BCR will be less than one. A change from a BCR of greater than one, to a value of less than one is sometimes termed the 'switch-over' point.

Table 6.8. Land Expectation Values per hectare for discount rates between 2 and 5 per cent are presented. For 0 per cent the NPV/rotation length (forest rents) are given. The low range of yield class is assumed.

	DISCOUNT RATE				
Low yield class range	0%	2%	3%	4%	5%
Management system	Forest rent	LEV	LEV	LEV	LEV
Sitka spruce plantation	97.35	1675	279	-322	-606
Japanese larch plantation	75.41	1303	182	-315	-567
Douglas fir plantation	141.1	2922	829	-103	-586
Douglas fir/oak plantation	137.1	2819	854	13	-400
Beech plantation	83.99	326	-608	-930	-1057
Oak plantation	102.6	1188	-27	-466	-647
Oak/ash/cherry	117.9	1967	381	-257	-545
Ash/sycamore shelterwood	59.30	1496	632	250	58
Re-coppice neglected oak	13.00	566	257	111	37
Neglect to oak/ash group	108.0	1915	763	366	198
Beech natural regeneration	90.12	1183	193	-149	-281
Birch natural regeneration	40.96	1427	824	556	415

Table 6.9. Benefit-Cost Ratios for discount rates between 0 and 5 per cent. Yield classes are assumed to be low. The low range of yield class is assumed.

Low yield class range Management system	DISCOUNT RATE 0% BCR	 2% BCR	 3% BCR	 4% BCR	 5% BCR
Sitka spruce plantation	4.67	1.75	1.15	0.80	0.59
Japanese larch plantation	3.98	1.56	1.10	0.81	0.62
Douglas fir plantation	5.64	2.12	1.39	0.95	0.67
Douglas fir/oak plantation	8.32	2.56	1.51	1.01	0.75
Beech plantation	5.52	1.15	0.68	0.49	0.40
Oak plantation	6.78	1.71	0.98	0.69	0.55
Oak/ash/cherry	7.83	2.11	1.24	0.83	0.64
Ash/sycamore shelterwood	5.92	2.34	1.66	1.28	1.07
Re-coppice neglected oak	12.8	6.07	4.02	2.54	1.57
Neglect to oak/ash group	13.79	3.30	2.00	1.50	1.28
Beech natural regeneration	8.67	1.87	1.16	0.86	0.74
Birch natural regeneration	6.72	3.08	2.25	2.11	1.88

Table 6.10. Land Expectation Values per hectare for discount rates between 2 and 5 per cent are presented. For 0 per cent the NPV/rotation length (forest rents) are given. The medium range of yield class is assumed.

Medium yield class range Management system	DISCOUNT RATE 0% Forest rent	 2% LEV	 3% LEV	 4% LEV	 5% LEV
Sitka spruce plantation	231.2	5952	2522	990	200
Japanese larch plantation	181.3	5243	2427	1110	388
Douglas fir plantation	273.2	7340	3209	1326	328
Douglas fir/oak plantation	235.4	5030	1966	688	50
Beech plantation	196.2	2611	325	-498	-836
Oak plantation	196.2	2611	325	-498	-836
Oak/ash/cherry	210.4	2362	294	-364	-602
Ash/sycamore shelterwood	181.7	4648	2087	998	472
Re-coppice neglected oak	35.06	746	286	98	9
Neglect to oak/ash group	206.0	3303	1286	601	317
Beech natural regeneration	202.9	3474	1124	278	-64
Birch natural regeneration	69.32	2495	1429	937	667

Table 6.11. Benefit-Cost Ratios for discount rates between 0 and 5 per cent. The medium range of yield class is assumed.

Medium yield class range Management system	0% BCR	DISCOUNT RATE 2% BCR	3% BCR	4% BCR	5% BCR
Sitka spruce plantation	8.90	3.65	2.40	1.62	1.14
Japanese larch plantation	6.70	3.25	2.32	1.69	1.26
Douglas fir plantation	9.18	3.78	2.50	1.69	1.18
Douglas fir/oak plantation	17.76	3.78	2.18	1.43	1.03
Beech plantation	11.02	2.22	1.17	0.73	0.53
Oak plantation	16.77	2.41	1.16	0.75	0.58
Oak/ash/cherry	16.42	2.98	1.60	1.01	0.74
Ash/sycamore shelterwood	16.26	5.16	3.19	2.13	1.56
Re-coppice neglected oak	22.04	7.68	4.36	2.36	1.14
Neglect to oak/ash group	31.80	4.97	2.69	1.82	1.44
Beech natural regeneration	17.44	3.55	1.95	1.25	0.94
Birch natural regeneration	9.06	4.66	3.57	2.87	2.42

Table 6.12. Land Expectation Values per hectare for discount rates between 2 and 5 per cent are presented. For 0 per cent the NPV/rotation length (forest rents) are given. The high range of yield class is assumed.

High yield class range Management system	0% Forest rent	DISCOUNT RATE 2% LEV	3% LEV	4% LEV	5% LEV
Sitka spruce plantation	367.4	10542	4997	2482	1155
Japanese larch plantation	315.8	10287	5313	2963	1657
Douglas fir plantation	395.3	11722	5655	2849	1355
Douglas fir/oak plantation	280.6	6731	2866	1225	397
Beech plantation	289.5	4445	1090	-136	-635
Oak plantation	260.9	3408	734	-154	-471
Oak/ash/cherry	291.8	5712	2037	599	-51
Ash/sycamore shelterwood	358.2	9736	4599	2376	1281
Re-coppice neglected oak	60.83	2088	1130	666	409
Neglect to oak/ash group	312.0	5778	2372	1125	578
Beech natural regeneration	296.7	5308	1882	638	128
Birch natural regeneration	127.8	4348	2399	1496	1013

Table 6.11. Benefit-Cost Ratios for discount rates between 0 and 5 per cent. The medium range of yield class is assumed.

	DISCOUNT RATE				
High yield class range Management system	0% BCR	2% BCR	3% BCR	4% BCR	5% BCR
Sitka spruce plantation	13.00	5.69	3.71	2.55	1.78
Japanese larch plantation	10.20	5.41	3.88	2.84	2.12
Douglas fir plantation	12.16	5.44	3.64	2.49	1.76
Douglas fir/oak plantation	21.80	4.72	2.72	1.76	1.25
Beech plantation	16.56	3.08	1.57	0.93	0.64
Oak plantation	20.56	3.03	1.48	0.89	0.67
Oak/ash/cherry	22.32	4.25	2.26	1.38	0.97
Ash/sycamore shelterwood	30.68	9.72	5.82	3.69	2.52
Re-coppice neglected oak	37.50	19.7	14.3	10.2	7.28
Neglect to oak/ash group	47.69	7.94	4.12	1.53	1.80
Beech natural regeneration	26.32	4.90	2.57	1.57	1.12
Birch natural regeneration	15.57	7.35	4.65	3.99	3.15

The least 'natural' coniferous plantations perform very well in the analyses based on net LEVs, especially between discount rates 2 and 4 per cent inclusive, at both the medium and high productivity levels. But the magnitude of LEVs is much lower for these systems at the low productivity levels, and they decrease dramatically with increasing discount rate. The corresponding BCR 'switch-over' points for these options at both medium and high productivity levels are in excess of 5 per cent. Obviously the switch-over point will occur between lower discount rates (3 and 4 per cent) if low productivity levels are assumed. The values for forest rent will often suggest a financial advantage for the 'less natural' forestry systems since higher levels of productivity for conifers are likely to be compared to lower levels of productivity for broadleaved species.

It is perhaps of greater significance that the more 'natural' management options appear very attractive if BCRs rather than LEVs are examined; this is often the effect of having low establishment costs. In addition, switch-over points for the BCRs are often in excess of 5 per cent for *all* productivity levels. Rising BCR values are obtained for a particular discount rate with increasing productivity levels. Obviously some management options have the desirable combination of low establishment costs combined with high revenues for the timber. But there are often limitations for some of these options as they assume certain woodland conditions in the first place. For instance the success of re-coppicing, and natural regeneration is largely dependent on the existing woodland. Ash/sycamore shelterwood and oak/ash group systems rely, at least in part, on natural regeneration. The natural regeneration of beech is often unreliable and the poorer BCRs are consequently due to increased establishment costs. Birch natural regeneration performs well (both in terms of LEV and BCR). However grants are included in Tables 6.8-6.12 and these play an important role in the outcomes. Should grants be unavailable for this system of management, the BCR would switch-over at between 2 and 3 per cent because of the reliance on the assumed lower value of the produce. This also accounts for the low values shown by the use of forest rent. However, LEVs remain positive at a discount rate of 4 per cent for medium productivity. These findings concur very well with those published by Leslie (1989) which represent averages for all temperate regions.

It is clear that new plantations of oak or beech perform poorly at all productivity levels using both LEVs and BCRs. LEVs are often positive for beech and oak plantations up to a discount rate of 3 per cent for both medium and high productivity levels and consequently BCRs often switch-over between discount rates of 2 and 3 percent for both of these productivity levels. Consideration of forest rent, however, produces a more favourable result with values similar to the 'more natural' broadleaved options being attained, assuming comparable productivity levels. Perhaps it is for investments such as these, where the value, both market and non-market, to future generations is likely to exceed present value estimates, that less stringent economic criteria should be employed (a lower discount rate applied to take account of non-market benefits). Are we already beginning to witness this with the proposed, and actual, broadleaved plantings in 'community' forests?

6.5.6 Recommended financial appraisal for 'natural' management.

Pre-investment management decisions have been analysed by three different methods: LEVs, BCRs and forest rents. Forest rent provides a measure of the average annual net revenue which is often more useful than the net revenue per rotation (NPV at 0 per cent discount rate) as the bias of rotation length is removed. Its use as a criterion for the selection of investments is traditionally confined to forests of normal age-structure, with annual costs for planting an area being met by revenues from felling another equal area in the same year. Invested capital is not tested against any real rate of return. Forest rent is therefore of dubious value in deciding between individual investments especially if they do not meet the age-class normality constraint.

The choice between LEVs and BCRs depends, according to economic theory, on the amount of capital available for the initial investment. If funds are restricted and insufficient to undertake the management option yielding the largest LEV for a given discount rate, then examination of the BCRs for the affordable investments is used. The management option yielding the highest BCR represents the most favourable option (Price *op. cit.*.).

In practice, the selection between profitable 'natural' management options will be dictated by the condition of the existing woodland. The possibilities should, perhaps, be analysed by the use of BCRs since many of these options can be regarded as investments with limited capital, simply because they often require less, and non-market costs of management intensification by the use of 'less natural' systems are often ignored. This approach is supported by the fact that using an LEV (or NPV) tends to favour alternatives involving intensification of management (with no guarantee of sustainable production), increased investment capital and a reduction of rotation lengths, rather than a more efficient use of an existing resource by 'natural' management. These factors suggests that BCRs should be more widely employed for this purpose.

6.6 Economic implications of increased planting densities for oak.

This section highlights the financial implications of increased planting density of oak on its profitability. The study is part of a wider discussion by Savill and Spilsbury (1991) that argues a case for closer spacing in oak plantations.

The effect of implementing increased planting densities on the long-term profitability of growing oak in plantations was analysed by the use the woodland economics computer program (Crockford *et al. op. cit.*; Spilsbury *op. cit.*). Land expectation values (LEVs), benefit-cost ratios (BCRs) and net undiscounted revenues were calculated. The use of LEVs and BCRs in assessing the profitability with respect to the 'less intensive' forms of forest management has been discussed in section 6.6. The analyses assumed a yield class of 5 m^3 ha^{-1} $year^{-1}$, management costs of a medium (national average) value, grants from the Woodland Grant Scheme at the rate payable for areas of 10 hectares or more, and a discount rate of 3 per cent. Average prices for timber and fuel-wood were assumed for the wider spaced oak (1100 and 2500 stems per hectare), whilst high timber prices and low fuel-wood prices were assumed for planting densities of 5000, 6250, and 7500 stems per hectare. The results of these analyses are shown in Table 6.12.

LEVs are expressed in terms of £ per hectare per rotation (in perpetuity) and show a decrease associated with the increasing planting density. The BCRs show a similar pattern across the range of planting densities. The net undiscounted revenues associated with these planting densities are also presented to highlight the assumption of the greater returns expected from management that makes use of higher planting densities. For the highest planting density of 7500 stems/ha (in the example) the long-term profitability of oak plantations is lowest. But for densities which, it is assumed, would still produce the benefits of competition in the early years of development (5000 stems/ha) the effect of greater establishment costs on the long-term profitability is fairly small and a positive LEV is still produced at a discount rate of three per cent. Increasing the planting density to 6250 stems/ha produces an LEV that is just negative at the same discount rate.

Table 6.12. Land expectation values and benefit-cost ratios for oak plantations at a 3 per cent discount rate at varying levels of planting density.

Planting density	1100	2500	5000	6250	7500
Land expectation value	445	294	126	-59	-244
Benefit-cost ratio	1.35	1.19	1.07	0.97	0.89
Net undiscounted revenue	25398	25244	33564	33376	33189

Another perhaps more empirical analysis that can be used as basis for comparison, is to examine the estimated revenues produced by final felling. Consider two crops of oak, one grown as stated by Jobling and Pearce (*op. cit.*) for freely grown oak (Yield class 6), where the mean dbh is ≈ 60 cm at 100 years, compared with the mean dbh of 43.6 cm for Yield Class 6 from a crop grown in accordance with the management tables (Hamilton and Christie *op. cit.*). Jobling and Pearce predict (from stands less than 40 years old) that timber heights of 100 year old trees are 16 m with mean height of 23.6 m although pruning is only practicable up to 6 m in practice. Whilst the stated diameter growth is entirely possible, we content that to expect such a substantial timber height is unrealistic. Our measurements indicate that for trees grown at wider spacing a timber height of 8 m is the maximum mean value that can be reasonably expected. Using the estimates of total volume to 7 cm top diameter presented by Corbyn *et al.* (1988), and the number of trees per hectare from the free grown and conventional management tables the analysis in Table 6.13 can be constructed. The final revenues expected from the two systems would be £7833 per hectare for free grown oaks and £16635 per hectare for the high forest oak.

Table 6.13. A comparison of the final crop of trees for a 100 year rotation of Yield Class 6 oak under free growth and high forest management conditions.

	Free growth	High forest
Mean dbh (cm)	60	43.6
Top height (m)	23.6	25.2
Timber height (m)	8	16
Number per hectare	62	156
Stem volume (m^3)	1.66	1.63
Branchwood volume (m^3)	2.40	0.42
Total tree volume (m^3)	4.06	2.05
Total stem volume/ha (m^3)	102.92	254.28
Total branchwood volume/ha (m^3)	148.8	65.52
Total tree volume/ha (m^3)	251.72	319.8
Value of total stem wood (£63.1/m^3)	£6494	£16045
Value of total branchwood (£9/m^3)	£1339	£590
Total value of final felling	£7833	£16635

It is apparent that there is a trade-off between the likely benefits of increased planting density and the financial constraints of increased planting costs. The benefits include greater choice of individuals for the final crop, earlier closure of the canopy (resulting in an earlier reduction in weeding), and the production of less branchy oak of higher commercial value. The major disadvantage is the reduction of the net discounted revenue due to the increased costs occurring at the beginning of the rotation. Costs at the beginning of a rotation are highly disfavoured by discounting analyses.

Whether a potential investor will plant, and at what planting density, will to some extent depend upon individual financial circumstance. For example the higher rates of WGS payment can offset the greater costs and have a substantial effect on magnitude of the LEV. If the WGS grant rate corresponding to areas greater than 1.0 ha and smaller than 2.9 ha is substituted into the example shown for a planting density of 6250 stems/ha (Table 2), the LEV increases from £-51 to £331 per hectare per rotation, the same grant at a planting density of 7500 would increase the LEV from £-266 to £147 per hectare per rotation. For those able to benefit from the Farm Woodland Scheme or Set-Aside Scheme payments the limitation of increased establishment costs is further reduced.

Proposing an increase in establishment costs to a forestry sector that has yet to adjust fully to the significant changes in investment incentives that were instituted in the 1988 budget is unlikely to be immediately popular. Yet, it is very probable that the increased cost will be more than offset by the production of timber of greatly superior quality. The calculations of timber revenues are a conservative estimate of this anticipated benefit.

6.7 Conclusions of planting density analysis.

It is apparent that much higher planting densities than those prevailing at present (≈ 1100 stems/ha) are required if stems of greater length and quality are to be grown (Savill and Spilsbury *op.cit*), but it remains unclear what the minimum planting density is to achieve good form with maximum economy because the relationship between the early development of form to its later development has not been thoroughly investigated. However, the economics of growing oak would not be greatly impaired, and indeed stand to gain much by planting at densities of between 5000 and 6250 stems/ha (1.27 x 1.27 m and 1.4 x 1.4 m).

CHAPTER 7. Summary and conclusions for PART 2.

Part 2 has been concerned with the development and use of a computer model for examining the relative profitability of a wide variety of woodland management systems. This Chapter aims to summarise the work, its findings and limitations, then proceed to suggestions for further study.

7.1 The reasons for the study of forest economics

There will always be decisions taken by potential investors between differing courses of action where financial returns are of importance. The assessment of financial viability in forestry is both arduous and time consuming if performed manually. Comparison between different forest management options is not commonly attempted by those unfamiliar with the techniques used in forest economic and financial analysis. No computer models to simplify these analyses have been produced previously in a form that is easy to use, and offers many thousands of possible comparisons.

With a political climate that is increasingly interested in the reduction of agricultural over-production and 'environmental' issues, and with significant changes in grant and taxation legislation, typical small-scale investors (eg farm woodland owners) require an easy method of obtaining reliable financial advice concerning potential investment in woodlands. The model produced by this study is of particular value for this purpose.

7.2 Summary of uses for the economics model.

The model was originally designed to aid employees of the Agricultural Development and Advisory Service (ADAS) in advising farmers on possible forestry investments. The requirements were to design a simple easy-to-use computer program that accurately reflected the relative profitability of forestry investments under a range of financial conditions. To this end the model was successful in meeting its objectives, although the extent to which ADAS have used it remains unknown.

Aside from the primary objective of providing a useful program for advisory purposes, there are two further applications; research and teaching.

Research work has made use of the ease of producing large numbers of comparisons to identify general trends in the profitability of management systems under varying conditions of grant rate, productivity, market prices and management costs Crockford *et al.* (1987b). This was further highlighted when the model was updated as a result of the 1988 budget. The structure of the original model facilitated the rapid inclusion of the altered financial circumstances and it was possible to compare the two models and assess the impact of the changes in forestry taxation legislation and grant eligibility (Spilsbury and Crockford 1989). A wide range of management options from the highly capital intensive conifer plantations to the more 'natural' regeneration and neglected woodland conversion options were considered. This provided an opportunity to investigate the potential for 'natural' management (Spilsbury 1990). There is also considerable flexibility for altering the default assumptions for each management option in terms of the establishment costs. These can be varied to suit individual circumstances or to examine the financial implications of higher costs early in a rotation.

The model has also proved to be particularly useful for the purposes of teaching. It is possible to examine quite complex financial scenarios quickly and easily, and determine the effects of altering any of the major variables on the outcome of the analyses. This provides an idea of the relative importance of each variable both within and between management options. For instance the effect of choosing a different discount rate (or eliminating discounting altogether), whilst holding other variables constant, can easily be investigated. The summary cash flow provides useful information concerning standard management practices and gives estimates of the branchwood component expected from the management option.

7.3 A summary of the findings produced from the use of the model.

The original version of the economics model was produced before the 1988 budget and this version highlighted the benefits available from the provision of tax relief on expenditure (schedule D taxation) followed by transfer to schedule B taxation before the revenue generating stages of the crop. Under the prevailing fiscal conditions grants were only of sufficient magnitude to offset some of the costs of establishment.

The production of a modified model in response to the changes instituted as a result of the 1988 budget provided an opportunity to assess immediately the impact of these changes on the profitability of management options. In general, those who were in receipt of income tax relief at rates over 45 per cent have a reduced incentive to invest in forestry, however to less wealthy investors the incentives have increased marginally. It is concluded that planting rates will reduce as a result, because the immediate incentive to establish new investments has been removed. For woodland establishment on agricultural land that qualifies for Farm Woodland Scheme or Set-Aside grants, there has been a marked increase in the long-term profitability. The incentives would be ideal were they available for all forest planting. However, they have been proposed with the aim of reducing agricultural overproduction and in this respect it is an objective that will have little, if any, chance of success.

Removal of forestry investment incentives based on income tax rates has meant that inherently profitable management options that were not able to benefit from tax relief on expenditure (eg oak/ash shelterwood systems, ash sycamore shelterwood systems or some of the natural regeneration options) appear all the more attractive in present financial circumstances. This effect is best highlighted by using a measure of the efficiency of investment, Benefit Cost Ratios. It is suggested that there has been too much emphasis on applying maximum magnitude of revenue criteria, often from bare ground, whilst the possibilities for more 'natural' management have been neglected. Not only is the efficiency of investment overlooked, but also the present value of neglected woodland (not included in the analyses) and the likely non-market benefits (also not included!). It is suggested that Benefit Cost Ratios are applied, rather than Land Expectation Values, in circumstances where there are possibilities of adopting such management.

The final study was to determine the stocking density at which planting oak would produce improvements in timber quality through greater competition during development and the provision of greater choice in selective thinnings, without becoming financially prohibitive. The post-1988 budget version was used and establishment costs were altered in accordance with the increased costs of higher planting density. The advantage gained from the close spacing was expressed as a higher price for the timber produced. The results indicated that the most suitable planting density should be between 5000 and 6250 stems per hectare. At such a density the conservative estimates of profitability are not drastically reduced and a return on investment of approximately 3 per cent is likely. If the assumption of increased quality of timber is correct then rates of return are likely to be higher than indicated by this study. Current practices in private woodlands (Miller *et al.* 1988a, 1988b) are between 1000 and 1200 stems per hectare and this is likely to be inadequate for the production of quality timber. The government should be advised that any alteration in the rate payable by grant schemes for planting should make provisions to encourage closer spacings for oak, and an attempt has been made to do this by publishing the findings (Savill and Spilsbury 1991).

7.4 The ephemeral quality of financial analysis.

One of the foremost limitations of any investigation of financial scenarios is the ephemeral nature of the analysis. A common concept in the appraisal of forestry investments is that of present values. By definition a present value for a cost or benefit is specific to the time at which the analysis was performed. For the purpose of examining the *relative* profitability of different management options this is of less importance if the relative value of costs and benefits, in real terms, remain fairly constant. The change of the real value is, however, very important if an absolute estimate of present worth is required. In the course of the development of the economics program, for example, the original survey of establishment costs and timber prices were inflated from the initial 1986 values to 1988 values to take account of the change in the real value of these costs and benefits. Clearly to continue to update the model in this manner would be inadvisable because the assumption of constant relative values between costs and benefits is unlikely to be reliable given the relative increase in the price of timber in real terms.

Present (1991) prices are likely to differ from those even in the updated model. Therefore economic models and the analyses produced by them have only a limited duration of relevance. The 1988 budget demanded that all previous estimates of profitability be reassessed under the new fiscal arrangements.

7.5 Limitations of the computer program and suggestions for an improved version.

The program has several aspects that limit its usefulness for purposes of research, teaching and use in advisory work.

Perhaps the most obvious limitation is the supposition that the potential investments are always assessed on the magnitude of the Land Expectation Values produced. Other criteria may apply, although financial investigations presume that some form of profit maximisation is important in decision-making. Future work to produce a similar model should provide for several methods of financial appraisal; Land Expectation Values, Net Discounted Revenues, Internal Rates of Return (IRR), Benefit-Cost ratios and Forest rent. These could be selected to suit the types of potential investment.

All levels of important variables are classified into a limited number of pre-set choices, and although a wide range is provided, there is no scope to enter specific values for the variables used. Is envisaged that future work would include pre-set management options in a similar form to the present model, for ease of use for those not familiar with forest management or economics. However there is a need to provide flexibility for the examination of 'tailor made' management options where species, prices, costs and most importantly (for discounted analyses) *timing* of operations may be input directly to suit individual circumstances or to investigate the economic implications of management practices. Having expressed the requirement for generating IRRs the inclusion of any discount rate will be required and this would also be useful for research purposes.

It would also be prudent, given the ephemeral nature of economic analyses, to provide a structure that would readily accommodate updating of the prices used. It is also recommended that computer program and its data be sufficiently small to fit on a computer 'floppy' 3 1/2" or 5 1/4" disk and function on IBM compatible microcomputers.

Like its predecessor the proposed model would largely be concerned with the assessment of investment priority *between* management options, and for examining the implications of different management strategy *within* a management option. It would not be designed to attempt to answer all economic questions (even if this were possible) since this would detract from its intended simplicity. For example, it would not be recommended that complex cost-benefit analyses be attempted nor risk considerations such as wind hazard classes, or *forecasts* of income for a forest region with different management options at different stages of development. In short a new model should allow examination and comparison of management options *by the consideration of one at a time* as an aid in the process of making decisions between potential investments.

Footnote:- It is hoped that the author will produce the updated model for the fulfilment of requirements for the Part 2 examination of the Institute of Chartered Foresters (subject to approval).

REFERENCES

Aber, J.D. and Melillo (1982). FORTNITE: A computer model of organic matter and nitrogen dynamics in forest ecosystems. ***University of Wisconsin Research Bulletin R3130*** 36p.

Aber, J.D., Botkin, D.B. and Mellilo J.M. (1979). Predicting the effects of different harvesting regimes on productivity and yield in northern hardwoods. ***Canadian Journal of Forest Research 9,*** 10-14.

Aber, J.D., Botkin, D.B. and Mellilo, J.M. (1978). Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. ***Canadian Journal of Forest Research 8,*** 306-315.

Adlard, P.G., Spilsbury, M.J. and Whitmore, T.C. (1988). Current thinking on modelling the tropical moist forest. ***IUFRO group conference proceedings, Malaysia 1988.***

Agren, G.I. (Editor) (1986). Predicting the consequences of intensive forest harvesting on long-term productivity. ***Swedish University of Agricultural Sciences. Report No.26.***

Alder, D. (1977). A growth and management model for coniferous plantations in East Africa. Unpublished ***D.Phil thesis, Oxford University.*** p 97.

Alder, D. (1980). Forest volume estimation and yield prediction. Volume 2 Yield prediction. ***FAO Forestry Paper 22/2.*** FAO, Rome, p viii + 194.

Anderson, M.L (1951). Distribution of Sessile Oak in the New Forest, Hampshire. ***Forestry 24 (2),*** 79-115 + map.

Assmann, E. (1970). ***The Principles of Forest Yield Study.*** Pergamon press, Oxford, p viii + 506.

Avery, T.E. and Burkhart, H.E. (1983). ***Forest measurements*** (3rd edition). McGraw-Hill,New York, p xviii + 331.

Bailey, R.L. and Dell, T.R. (1973). Quantifying diameter distributions with the Weibull function. ***Forest Science 19,*** 97-104.

Balfour, A. and Marwick, D.H. (1979). ***Programming in Standard FORTRAN*** *77.* Heinemann, London, p v + 388.

Belcher, D.M., Holdaway, M.R. and Brand G.J. (1982). A description of STEMS-the stand and tree evaluation and modelling system. ***USDA Gen. Tech. Rep. NC-79,*** p 18.

Bertalanffy, L. von (1951). Zu einer allegmeiner systemlehrer. ***Blatter fur Deutsche Philosophie 3 (4).***

Bormann, F.H. and Likens, G.E. (1979). ***Pattern and process in a forested ecosystem.*** Springer-Verlag, New York, p v + 253.

Botkin, D.B. Janak, J.F. and Wallis, J.R. (1972). Some Ecological consequences of a computer model of forest growth. ***Journal of Ecology 60,*** 849-872.

Bradley, R.T. Christie, J.M., and Johnston, D.R. (1966). Forest Management tables. ***Forestry Commission Booklet No 16,*** HMSO, London.

Brown, K.M. and Clarke, F.R. (Editors) (1980). ***Proceedings of the workshop held at the School of Forestry Lakehead University***, Thunder Bay, Ontario, p iii + 261.

Bruner, H.D. and Moser, J.W. (1973). A programmed Markov chain approach to prediction of diameter distribution in uneven-aged forest stands. ***Canadian Journal of Forest Research 3,*** 409-417.

Buchman, R.G. (1979). Mortality functions. In, A generalised forest growth projection system applied to the Lake States region. ***USDA. For. Serv. Gen. Tech. Rep. NC-49,*** p 47-55.

Buongiorno, J. and Michie, B.R. (1980). A matrix model of uneven-aged forest management. ***Forest Science 26 (4),*** 609-625.

Cameron, R.A.D. (1980). Stand structure, species composition and succession in some Shropshire woods. ***Field Studies 5,*** 289-306.

Campbell, H. (1981). Pine Operations Thinnings Scheduler Technical Documentation. The Growth Model. ***Western Australia Forestry Department, Research Note, 29 p.***

Campbell, R.G. Ferguson, I.S. and Opie J.E. (1979). Simulating growth and yield of Mountain Ash stand: a deterministic model. ***Australian Journal of Forest Research 9,*** 189-202.

Chapman, D.G. (1961). Statistical problems in population dynamics. ***Proc. Fourth Berkley Symp. Math. Stat. and Prob.*** Univ. Calif. Press, Berkley, p 153-168.

Chapman, H.H. and Demeritt, D.B. (1936). ***Elements of forest mensuration.*** J.B Lyon Company, New York, p 451.

Christie, J.M. (1972). The characterisation of relationships between basic crop parameters in yield table construction. ***I.U.F.R.O. 3rd. conference advisory group of forest statisticians.***

Clements, F.E. (1936). Nature and structure of the climax. ***Journal of Ecology 24,*** 252-284.

Clements, F.E. (1916). Plant succession: An analysis of the development of vegetation. ***Carnegie Institute Publication 242,*** Washington D.C. p 512.

Clutter, J.L. (1963). Compatible growth and yield models for Loblolly pine. ***Forest Science 9 (3),*** 354-371.

Cooper, W.S. (1923). The recent ecological history of Glacier Bay, Alaska. ***Ecology, 93-128, 223-246, 355-365.***

Cousens, J.E. (1965). The status of the Penndunculate and Sessile Oaks in Britain. ***Watsonia 6 (3),*** 161-176.

Corbyn, I.N., Crockford, K.J. and Savill, P.S. (1988). The estimation of the branchwood component of broadleaved woodlands. ***Forestry 61 (3),*** 193-204.

Crockford, K.J. (1987). An evaluation of British woodlands for fuelwood and timber production. Unpublished ***D.Phil thesis, University of Oxford,*** p 219.

Crockford, K.J. Corbyn, I.N. and Savill, P.S. (1987a). An Evaluation of the Methodology for managing existing broadleaved and coniferous woodland for timber and energy production. ***Report for the U.K. Atomic Energy Authority. ETSU B1156.***

Crockford, K.J. Spilsbury, M.J. and Savill, P.S. (1987b). The relative economics of woodland management systems. ***Oxford Forestry Institute Occasional Paper No 35,*** p 64.

Curtis, R.O. (1967). Height-diameter and height-diameter-age equations for second-growth Douglas fir. ***Forest science 13,*** 365-375.

Curtis, R.O. (1967). A method of estimation of gross yield of Douglas fir. ***Forest science monograph, No 13*** p 1-24, Society of American Foresters.

Dale, V.H. and Gardner, R.H. (1987). Assessing regional impacts of growth decline using a forest succession model. ***Journal of Environmental Management 24 (1),*** 83-93.

Dale, V.H. and Hemstrom, M. (1984). CLIMACS: A computer model of forest stand development for western Oregon and Washington. ***U.S. Forest service research paper (Pacific northwest research station) PNW-327.***

Dale, V.H., Hemstrom, M. and Franklin, J. (1986). Modelling the long-term effects of disturbances on forest succession, Olympic peninsula, Washington. ***Canadian Journal of Forest Research 16 (1),*** 56-67.

Daniels, R.F. and Burkhart, H.E. (1988). An integrated system of forest stand models. ***Forest Ecology and Management 23,*** 159-177.

Daniels, R.F., Burkhart, H.E. and Clason, T.R. (1986). A comparison of competition measures for predicting growth of loblolly pine trees. ***Canadian Journal of Forest Research 16,*** 1230-1237.

Dawkins, R. (1976). ***The selfish gene.*** Oxford University Press. Oxford. p. xi + 225.

Dengler, A. (1939). Commentary on Oelkers's "Silviculture Pt IV Regeneration." ***Z. Forst. u. Jagdw, 71 (6) 307-317.***

Detwilter, R.P. and Hall C.A.S. (1980). The development of an empirically driven simulation model of carbon exchange between human-impacted tropical ecosystems and the atmosphere. ***Report of Symposium. The role of tropical forests on the world carbon cycle. USDE CONF-800350.***

Dolan, A.G. and Russell, B.P. (1985). ***Economic survey of private forestry: England and Wales. Establishment costs 32nd annual report for forest year 1983.*** Oxford Forestry Institute, Oxford.

Doyle, T.W. (1981). The role of disturbance in the gap dynamics of a montain rainforest: An application of a forest succession model. IN West, D.C. et al (Eds), ***Forest Succession: concepts and application.*** Springer Verlag pp. 56-73.

Draper, N.R. and Smith, H. (1966). ***Applied regression analysis.*** J Wiley and Sons, New York. p ix + 407.

Dudek, A. and Ek, A.R. (1980). A bibliography of worldwide literature on individual tree based forest stand growth models. ***Institute of Agric. & For., Minnesota Univ. Staff Paper No.12.*** p.30.

Eckstein, D. (1972). Tree-Ring research in Europe. ***Tree-Ring Bulletin 32,*** 1-18.

Edwards, P.N. and Christie, J.M. (1981). Yield models for management. ***Forestry Commission Booklet No. 48,*** HMSO, London, p 32.

Ek, A.R and Monserud, R.A. (1974). FOREST: A computer model for simulating the growth and reproduction of mixed species forest stands. ***Wisconsin University Research paper R 2635,*** p 13.

Ek, A.R. (1974). Nonlinear models for stand table projection in northern hardwood stands. ***Canadian Journal of Forest Research 4,*** 23-27.

Ek, A.R., Shifley, S.R. and Burk, T.E (Editors) (1988a). Forest growth modelling and prediction ***Volume 1.*** IUFRO conference proceedings Minneapolis 1987. U***SDA For. Serv. Gen. Tech. Rep. NC-120,*** p ix + 579.

Ek, A.R., Shifley, S.R. and Burk, T.E. (Editors) (1988b). Forest growth modelling and prediction ***Volume 2.*** IUFRO conference proceedings Miniapolis 1987. ***USDA For. Serv. Gen. Tech. Rep. NC-120,*** p vii + 580-1149.

Evans, J. (1982). Silviculture of broadleaf woodlands. ***Forestry Commission Bulletin No 62,*** HMSO, London.

Evert, F. (1971). Spacing studies, a review. Canadian Forest Service. ***Forest Management Institute Information Report.*** FMR-X-37.

Fennell, R. (1988). The evolution of rural policies in the European Community, agriculture, forestry and the environment. In ***Oxford Forestry Institute Occasional Paper No 38.***

Fletcher, J.M. (1986). X-rays for density and dendrochronology. ***Papers published 1970-1986. 110 papers bound for University of Oxford.***

Flewelling, J.W. and Pienaar, L.V. (1981). Multiplicative errors with lognormal errors. ***Forest Science 47, (2)*** 281-289.

Forestry Commission (1975). Forest Mensuration Handbook. ***Forestry Commission Booklet No 39,*** HMSO, London.

Forestry Commission (1985). Forestry Grant Scheme. ***Forestry Commission Leaflet,*** HMSO, London, p 12.

Forestry Commission (1985). Taxation of woodlands. ***Forestry Commission Leaflet No 12,*** HMSO, p 14.

Forestry Commission (1987). Broadleaved Woodland Grant Scheme. ***Forestry Commission Leaflet,*** HMSO, London, p 12.

Forestry Commission (1988). Woodland Grant Scheme. ***Forestry Commission Leaflet,*** HMSO, London, p 12.

Fricker J (1988). Unpublished B.Sc. research project. Brunel University.

Fries, J. (Editor) (1974). Growth models for tree and stand simulation. IUFRO working party S4.01-4. ***Proceedings of the meeting in 1973. Skogshgskolan: Royal Coll. For. Stockholm,*** Sweden p 379.

Fritts, H.C. (1976). ***Tree rings and climate.*** Academic Press, London, New York, p xii + 365.

Furnival, G.M. (1961). An Index for comparing equations used in constructing volume tables. ***Forest science 7 (4),*** 337-341.

Galea, E. (1988). Supercomputers and the need for speed. ***New Scientist 120,*** 50-55.

Gertner, G. (1987). Approximating precision in simulation projections: An efficient alternative to Monte Carlo methods. ***Forest Science 33 (1),*** 230-239.

Gertner, G. and Dzialowy, P. (1987). Effects of measurment errors on an individual tree based growth projection system. ***Canadian Journal of Forest Research 14,*** 311-316.

Gholz, H.L. (1982). Environmental limit on aboveground net primary production, leaf area, and biomass in vegetation zones of the Pacific Northwest. ***Ecology 63,*** 469-481.

Gleason, H.A. (1917). The structure and development of the plant association. ***Bulletin of the Torrey Botanical Club No. 43,*** p 463-481.

Gleason, H.A. (1927). Further views on the succession concept. ***Ecology 8,*** 299-326.

Gleason, H.A. (1939). The individualistic concept of the plant association. ***American Midland Naturalist 21,*** 92-110.

Grace, J.C. (1980). Computer modelling of individual tree growth. Unpublished ***D.Phil thesis for the University of Oxford.***

Gray, A.J, Crawley, M.J. and Edwards, P.J. (Editors) (1987). ***Colonisation succession and stability. The 26th symposium of the British Ecological Society.*** Blackwell Scientific, Oxford, p ix + 482.

Grimes, R.F. and Pegg, R.E. (1979). Growth data for a spotted gum-ironbark forest in south-east Queensland. ***Queensland Department of Forestry Technical Paper No 17,*** p 30.

Hahn, J.F. and Rolfe, A. (1979). Potential diameter growth equations. In. A generalised forest growth projection system applied to the Lake States region. ***USDA. Gen Tech. Rep. NC-49,*** p 22-26.

Hamilton, D.A. Jr (1990). Extending the range of applicability of an individual tree mortality model. ***Canadian Journal of Forest Research 20,*** 1212-1218.

Hamilton, G.J. and Christie, J.M. (1971). Forest management tables (metric). ***Forestry Commission Booklet 34,*** H.M.S.O., London; pp. 201.

Hamilton, G.J. and Christie J.M. (1974). Influence of spacing on crop characteristics and yield. ***Forestry Commission Bulletin No. 52,*** HMSO, p iv + 90.

Hanson C.O. (1913). Yield table for oak in the Dean forest. ***Quarterly Journal of Forestry 7,*** 269-279.

Hara, T. (1985). A model for mortality in a self-thinning plant population. ***Annals of Botany 55 (5),*** 667-674.

Harlow, W.M. and Harrar, E.S. (1969). ***Textbook on Dendrology.*** McGraw-Hill, New York.

Harper, J.L. (1977). ***Population biology of plants.*** Academic Press, New York, 892 p.

Harrison, A.F. and Ineson, P. (1987). Nitrogen cycling in a *Quercus/Fraxinus* (oak.ash) woodland in northern England, examined using the computer model FORTNITE. In The temperate forest ecosystem. ***Instiitute of Terrestrial Ecology Symposium No 20,*** (Editors, Yang Hanxi, Wang Zahn, Jeffers and Ward) p 115-123.

Harrison, A.F. and Ineson, P. (1988). Dynamic modelling of tree growth in a mixed-deciduous woodland: its significance for research and management. In ***Oxford Forestry Institute Occasional Paper No 37.*** Report of the Eighth meeting of The National Hardwoods Program, p 12-26.

Harrison, T.P. and Michie, B.R. (1985). A generalised approach to the use of matrix growth models. ***Forest Science 31 (4),*** 850-856.

Hart, C.E. (1979). ***Taxation of Woodlands.*** Published by the author.

Hilt, D.E. (1985). User's Guide to OAKSIM; an individual-tree growth and yield simulator for even-aged upland oak stands. ***USDA. For. Serv. Tech. Rep. NE-104.***

Horn, H.S. (1976) Succession. pp 187 -204 IN ***R. May (editor), Theoretical Ecology.*** Blackwell Scientific Publications, Oxford.

Horsfall, A.S. and Kirby, K.J. (1985). The use of permanent quadrats to record changes in the structure and composition of Wytham Woods, Oxfordshire. ***Research and survey in nature conservation No 1. Nature Conservancy Council.***

Hughes, G.A., and Sendak, P.E. (1985). Key algorithms in GRO2: A computer simulation model for predicting tree and stand growth. ***USDA For. Serv. Research paper NE-570,*** p 17.

Hummel, F.C. (1955). The volume-basal area line. ***Forestry Commission Bulletin No 24,*** HMSO, London, p vi + 84.

Hummel, F.C. and Christie,J.M. (1957). Methods used to construct revised yield tables for conifers in Great Britain. ***Forestry Commission report on forest research for the year ended March 1957,*** HMSO, London, p 137-141.

Hunt, R. (1982). ***Plant Growth Curves.*** Edward Arnold, London p viii + 248.

Jeffers, J.N.R. (1959). Experimental design and analysis in forest research. IUFRO. Almquvist and Wiksell, Stockholm p 172.

Jeffers, J.N.R. editor (1971). ***Mathematical models in ecology.*** Blackwell Scientific Publications, Oxford, p vii + 398.

Jeffers, J.N.R. (1978). ***An introduction to systems analysis with ecological implications.*** Edward Arnold, London, p x + 198.

Jeffers, J.N.R. (1982). Modelling. ***Outline studies in ecology*** Chapman and Hall, 80 p.

Jobling, J. and Pearce, M.L. (1977). Free-growth of oak. ***Forestry Commission Forest Record No 113,*** HMSO, London, p 17.

Jones, E.W. (1945). The structure and reproduction of the virgin forest of the north temperate zone. ***New Phytologist 44 (2),*** 130-148.

Kelpac, D. (1971). An experiment on displacement of height curves in even-aged penduncculate oak stands with respect to their age. ***Sumarski List 95 (5/6),*** 141-149.

Ker, J.W and Smith, J.H.G. (1955). Advantage of the parabolic expression of height-diameter relationships. ***Forestry Chronicle 31,*** 235-246.

Ker, J.W and Smith, J.H.G. (1957). Sampling for height-diameter relationships. ***Journal of Forestry 55 (3),*** 205-207.

Koop, H. (1989). ***Forest Dynamics SILVI-STAR: A comprehensive monitoring system.*** Springer Verlag, Berlin, p viii + 229.

Krebs C.J. (1972). ***Ecology, the experimental analysis of distribution and abundance.*** Harper & Row, New York, p ix + 694.

Lawrence, D.B. (1958). Glaciers and vegetation in southeastern Alaska. ***Amer. Sci. 8, 210-218.***

Larson. P.R. (1963). Stem form and development in forest trees. ***Forest science monograph; No 5,*** Society of American Foresters.

Leary, R.A. (1970). System identification principles in studies of forest dynamics. ***USDA Forest Service Research Paper. No NC-45,*** p 38.

Leary, R.A. (1979). In: ***USDA (1979)***

Leslie, A.J. (1989). On the economic prospects for natural management in temperate hardwoods. ***Forestry 62 (2),*** 147-165.

Li, C. (1988). Mathematical models in forest resource management planning - An integrated study of calibration, prediction and optimal decisions models. ***Sveriges Lantsbrukuniversitet. Institutionen fllr biometri och skogsindelning. Rapport 18.***

Linnard, W. and Gane, M. (1968). Martin Faustmann and the evolution of the Discounted Cash Flow. ***Commonwealth Forestry Institute paper No. 42.*** Oxford University. p.55. Two articles translated from the original German of 1849.

Liu, C.J. (1986). Rectifying radii on off-center increment cores. ***Forest Science 32 (4),*** 1058-1061.

Lorrain-Smith, R. (1988). ***The economic effectsd of the guidelines for the management of broadleaved woodland.*** A study carried out for the Timber Growers United Kingdom Ltd. p 167.

Lorrain-Smith, R. (1982). An economic analysis of silvicultural options for broadleaved woodland. Volume 2. ***Commonwealth Forestry Institute Occasional Paper No. 19,*** p 120.

Lynch, T.R. and Moser, J.W. (1986). A growth model for mixed species stands. ***Forest Science. 32 (3),*** 697-706.

McClaugherty, C.A., Aber, J.D. and Mellilo, J.M. (1982). The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems. ***Ecology 63 (5),*** 1481-1490.

Mellilo, J.M., Aber J.D. and Muratore, J.M. (1982). Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. ***Ecology 63 (3),*** 621-626.

Meyer, H.A. (1944). A correction factor for systematic error occurring in the application of the logarithmic volume equation. ***Pennsylvania State University Forest Research Paper No 7.***

Michie, B.R. and McCandless, F.D. (1986). A matrix model of oak-hickory stand management and valuing forest land. ***Forest Science 32 (3),*** 759-768.

Mielke, D.L., Shugart, H.H. and West, D.C. (1978). ***A stand model for upland forests of southern Arkansas. ORNL/TM-6255,*** Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Miles, J. (1979). Vegetation Dynamics. ***Outline studies in ecology.*** Chapman and Hall, 80 p.

Miles, J., Schmidt, W., Maarel, E. Van Der. (1988). Temporal and spatial patterns of vegetation dynamics.***Vegetatio 77,*** 3-201.

Miller, D.R., Butler, G. and Bramall, L. (1976). Validation of ecological systems models. ***Journal of Environmental Management, 4,*** 383-401.

Miller, F.R., Savill, P.S. and Kirk, C.F. (1988a). The broadleaved woodlands policy on the Forestry Commission estate. Unpublished report for Forestry Commission; pp.70.

Miller, F.R., Savill, P.S. and Kirk, C.F. (1988b). The broadleaved woodlands policy in privately owned woodlands. Unpublished report for Forestry Commission; pp.85.

Mitchell, A.F. and Hallett, V.E. (1985). Champion trees in the British Isles. ***Forestry Commission Research and Development Paper No 138,*** HMSO, London p 28.

Mitchell, H.L. and Chandler R.F. (1939). The nitrogen nutrition and growth of certain deciduous trees of the northeastern U.S. ***Black Rock Forest Bulletin No 11,*** p 94.

Mitchell, K.J. (1975). Dynamics and simulated yield of Douglas fir. ***Forest science monograph. No 17,*** p 39, Society of American Foresters

Mitchell, P.L. (1987). Ecological effects of forestry practices in long established woodland. ***A literature survey for the N.C.C. volume 1, p viii + 167,*** volume 2 (summary and appendices).

Monserud, R.A. and Ek, A.R. (1977). Prediction of understorey tree height growth in northern hardwood stands. ***Forest Science 23 (3),*** 391-400.

Montgomery, D.C. (1976). ***Design and analysis of experiments.*** J Wiley and Sons, New York, p xvi + 538.

Moore, P.D. and Chapman S.B. (Editors) (1986). ***Methods in plant ecology (second edition).*** Blackwell Scientific Publications, Oxford, p xiii + 589.

Morris, M.G. and Perring, F.H. (Editors) (1974). ***The British Oak, its history and natural history.*** E.W. Classey Ltd, Faringdon Berks, p 376.

Moser, J.W. (1974). A system of equations for the components of forest growth. In Fries, J. (Editor). Growth models for tree and stand simulation. IUFRO working party S4.01-4. ***Proceedings of the meeting in 1973. Skogshgskolan: Royal Coll. For. Stockholm,*** Sweden p 379.

Munro,D.D. (1984). Growth modelling for fast growing plantations. IN ***Proceedings IUFRO Symposium on Site and Productivity of Fast Growing plantations, Pretoria and Pietermaritzburg, South Africa, Volume 1, 334-344.***

Munro, D.D. (1974). Forest growth models. A prognosis. pp 7 - 21 IN Fries, J. (Editor) (1974). Growth models for tree and stand simulation. IUFRO working party S4.01-4. ***Proceedings of the meeting in 1973. Skogshgskolan: Royal Coll. For. Stockholm,*** Sweden p 379.

Newnham, R.M. (1964). The development of a stand model for Douglas fir. ***Ph.D Thesis Univ of B.C., Vancouver,*** p 201.

Nichols, G.E. (1923). A working basis for the ecological classification of plant communities. ***Ecology 4,*** 11-23, 154-172.

Oldeman, R.A.A. (1978). Architecture and energy exchange of dicotyledonous trees in the forest. p 525-560. IN ***Tropical trees as living systems. (Tomlinson and Zimmerman [Editors]), Cambridge University Press.***

Ovington, J.D. (1962). Quantitative Ecology and the woodland ecosystem concept. In ***Advances in Ecological Research 1. (Editor Cragg, J.B).***

Pastor, and Post, (1985). Influence of climate, soil moisture, and succession on forest carbon and nitrogen cycles.***Biogeochemistry 2, 13-27.***

Payendeh, B. (1983). Some applications of non-linear regression models in forestry research. ***Forestry Chronicle, 59 (10),*** 244-248.

Perry, T.O, Sellers, H.E. and Blanchard, C.O. (1969). Estimation of photosynthetically active radiation under a forest canopy with chlorophyll extracts and from basal area measurements. ***Ecology 50,*** 39-44.

Phipps, R.L., and Applegate, L.H. (1983). Simulation of management alternatives in wetland forests. p 311-339. In, ***Jorgensen, S.E, and Mitsch (Editors). Application of ecological modelling in environmental management, Part 4B,*** Elsevier, Amsterdam, Oxford etc, p viii + 438.

Pickett S.T.A and White P.S. (Editors) (1985). ***The ecology of natural disturbance and patch dynamics.*** Academic Press Inc, Orlando, p xiii + 472.

Pielou, E.C. (1969). ***An Introduction to Mathematical Ecology.*** Wiley-Interscience, New York, p 283.

Pienaar, L.V., and Turnbull, K.J. (1973). The Chapman-Richards generalisation of Von Bertalanffy's growth model for basal area growth and yield in even-aged stands. ***Forest Science 19 (1),*** 2-22.

Pranjic, A. (1970). Stand height curves for Quercus robur. ***Sumarski List 94 (7/8),*** 201-220.

Price, C. (1989). ***The theory and application of forest economics.*** Blackwell, Oxford, New York, p, vi + 402.

Prodan, M. (translated by Gardiner, S.H.) (1961). ***Forest Biometrics.*** Pergammon Press, Oxford. p xi + 447.

Pryor, S.N. (1982). An economic analysis of silvicultural options for broadleaved woodland. Volume 1. ***Commonwealth Forestry Institute Occasional Paper No. 19,*** p 120.

Pryor, S.N. (1985). An evaluation of silvicultural options for broadleaved woodland. Unpublished ***D.Phil thesis, University of Oxford,*** p 247.

Reichle D.E. editor (1981). ***Dynamic properties of forest ecosystems; IBP Volume 23,*** Cambridge: Cambridge University Press, p xxvi + 683.

Reineke, L.H. (1933). Perfecting a stand density index for even-aged forests. ***Journal of Agricultural Research 46,*** 627-638.

Rennolls, K. and Peace, A. (1986). Flow models of mortality and yield for unthinned forest stands. ***Forestry 59 (1),*** 47-58.

Rennolls, K. and Blackwell, P (1986). An Integrated Forest Process Model: its calibration and predictive performance. ***Forestry Commission Research and Development Paper No 140,*** HMSO, London.

Revilla, A.V. (1981). A review of growth and yield studies on the tropical mixed forests of the Asia region. ***Paper to joint FAO/IUFRO meeting on growth and yield studies. Jan 26-30th.***

Reynolds, M.R., Burkhart, H.E. and Daniels, R.F. (1981). Procedures for statistical validation of stochastic simulation models. ***Forest Science 27,*** 349-364.

Reynolds, M.R. and Chung, J. (1986). Regression methodology for estimating model prediction error. ***Canadian Journal of Forest Research 16 (5),*** 931-938.

Richards, F.J. (1958). A flexible growth function for empirical use. ***Journal of Experimental Botany 10 (29),*** 290-300.

Roberts, N., Anderson, D.F., Deal, R.M., Garet, M.S., & Shaffer, W.A. (1983). ***Introduction to computer simulation, a system dynamics modelling approach.*** Addison-Wesely, Reading, Massachusetts, p xii + 562.

Runkle, J.R. (1985). Disturbance regimes in temperate forests. In ***The ecology of natural disturbance and patch dynamics (Editors Pickett, S.T.A. and White, P.A.) p.17-34.***

Sachs,D. and Sollins, P. (1986). Potential effects of management practices on nitrogen nutrition and long-term productivity of western hemlock stands. ***Forest Ecology and Management 17,*** 25-36.

Savill, P.S. and Spilsbury, M.J. (1991). Growing oaks at closer spacing. ***Forestry 64 (4),*** (in press).

Shugart, H.H. (1984). ***A theory of forest dynamics. The ecological implications of forest succession models.*** Springer-Verlag, New York, p ix + 278.

Shugart, H.H, Crow, T.R. and Hett, J.M. (1973). Forest succession models: A rationale and methodology for modelling forest succession over large regions. ***Forest Science 19,*** 203-212.

Shugart, H.H. and Noble, I.R. (1981). A computer model of succession and fire response of the high-altitude Eucalyptus forest of the Brindabella range, Australian Capital Territory. ***Australian Journal of Ecology 6,*** 149-164.

Shugart, H.H. and West, D.C. (1979). Size and pattern of simulated forest stands. ***Forest Science 25,*** 120-122.

Shugart, H.H. and West, D.C. (1977). Development of an Appalachian forest succession model and its application to assessment of the impact of the chestnut blight. ***Journal of Environmental Management 5,*** 161-179.

Shugart, H.H., Hopkins, M.S., Burgess, I.P. and Mortlock, A.T. (1981). The development of a successional model for tropical rainforest and its application to assess the effects of timber harvest at Wiangarree State Forest N.S.W. ***Journal of Environmental Management 11,*** 243-265.

Siegel, A.F. (1988). ***Statistics and data analysis.*** J Wiley & Sons, New York, p xxv + 518.

Smalley, G.W. and Bailey, R.L. (1974). Yield tables and stand structure for Loblolly pine plantations in Tennessee, Alabama, and Georgia highlands. ***USDA. Forest research paper SO-96 Southern forest experiment station.***

Smol'yanov, A.N. (1983). Mathematical models of height growth of young oak plantations on felled areas. ***Lesnoi Zhurnal 5,*** 11-14.

Sollins, P., Reichle, D.E. and Olson, J.S. (1973). Organic matter budget and model for a southern Appalachian *Liriodendron* forest. ***EDFB/IBP-73/2. Oak Ridge National Laboratory,*** Oak Ridge, Tennessee.

Spilsbury, M.J. (1987). Woodland Management Decisions a User's Guide. ***Report for the energy technology division of the U.K. Atomic Energy Authority. ETSU B1156.***

Spilsbury, M.J. (1988). Woodman III - A User's Guide. ***Report to the energy technology division of the U.K. Atomic Energy Authority. ETSU B1156.***

Spilsbury, M.J. and Crockford K.J. (1989). Woodland economics and the 1988 Budget. ***Quarterly Journal of Forestry 83 (1),*** 25-32.

Spurr, S.H. (1952). Origin of the concept of forest succession. ***Ecology 33,*** 426-427.

Spurr, S.H. and Barnes, B.V. (1975). ***Forest Ecology, 2nd edition.*** Ronald Press, New York; p x + 690.

Spurr, S.H. and Barnes, B.V. (1981). ***Forest Ecology 3rd edition.*** J Wiley & Sons, New York, p x + 687.

Standing, I.J. (1987). Ancient and notable trees in and around Dean, Part II. ***The New Regard. Journal of the Forest of Dean local history society. No.3,*** 25-34.

Standing, I.J. (1986). Ancient and notable trees in and around the Dean. ***The New Regard. Journal of the Forest of Dean local history society. No 2,*** 3-21.

Sykes, J.M. and Barr, C.J. (1973) Dry weight and mineral composition estimates for 15 year old mixed hardwood coppice in Roudsea Wood. ***Merlewood Research and Development Paper 50,*** Institute of Terrestrial Ecology.

Sykes, J.M. (1990) Development of the FORET woodland dynamics model. In ***Annual Report of the Institue of Terrestrial Ecology 1989.***

Tansley, A.G. (1935). The use and abuse of vegetational concepts and terms. ***Ecology 16,*** 284-307.

Taylor, G. and Davies, W.J. (1985). The control of leaf growth of *Betula* and *Acer* by photoenvironment. ***New Phytologist 101, 259-268.***

Tharp, M.L. (1978). Modelling major perturbations on a forest ecosystem. University of Tennessee M.S. Thesis. In ***Shugart, H.H. (1984). A Theory of forest dynamics.***

Timber Growers U.K. (1988). ***Forestry Planting on Agricultural Land. Fact Sheet No 9.***

Trorey, L.G. (1932). A mathematical method for the construction of diameter height curves based on site. ***Forestry chronicle 8,*** 121-132.

Tucker, J.J. and Fitter A.H. (1981). ***The Naturalist 106,*** 3-14.

USDA (1979). A generalised forest growth projection system applied to the Lake States region. ***USDA Forest Service. General Technical report NC-49*** p 96.

Usher, M.B. (1967). A structure for selection forests. ***Sylva 47,*** 6-8.

Usher, M.B. (1966). A matrix approach to the management of renewable resources, with special reference to selection forests. ***Journal of Applied Ecology 3,*** 355-367.

Vanclay J.K. (1983). Techniques for modelling timber yield from indigenous forests with special reference to Queensland. Unpublished ***M.Sc. Thesis, Oxford University.***

Vanclay, J.K. (1989). A growth model for North Queensland rainforests. ***Forest Ecology and Management 27,*** 245-271.

Vanclay (1990) Untitled book manuscript (in press).

Wahlenberg, W.G. (1941). Methods for forecasting timber growth in irregular stands. ***USDA Technical Bulletin. No.796,*** p 55.

Waring, R.H. and Schleisinger, W.H. (1985). ***Forest ecosystems, concepts and management.*** Academic Press, New York, Oxford, p xiii + 340.

Warren, W.G. (1980). On removing the growth trend from dendrochronological data. ***Tree-Ring Bulletin 40,*** 35-44.

Watt, A.S. (1925). On the ecology of British beech woods with special reference to thei regeneration. II The development and structure of beech communities on the Sussex Downs. ***Journal of Ecology 13, 27-73.***

Watt, A.S. (1947). Pattern and process in the plant community. ***Journal of Ecology 35, 1-22.***

Waters W.T. and Christie J.M. (1958). Provisional yield tables for oak and beech in Great Britain. ***Forestry Commission; Forest Record No. 36,*** p 31.

Weber, L.A., Ek, A.R. and Droessler, T.D. (1986). Comparison of stochastic and deterministic mortality estimation in an individual tree based stand growth model. ***Canadian Journal of Forest Research 16 (5),*** 1139-1141.

Weinstein, D.A., Shugart H.H. and West, D.C. (1982). ***The long-term nutrient retention properties of forest ecosystems: A simulation investigation. ORNL/TM-8472,*** Oak Ridge, Tennessee, 145 p.

West D.C., Shugart, H.H. and Botkin, D.B. (Editors). (1981). ***Forest succession concepts and application.*** Springer-Verlag, New York, p xv + 517.

West, D.C., McLaughlin, S.B. and Shugart H.H. (1980). Simulated forest response to chronic air pollution stress. ***Journal of Environmental Quality 9,*** 43-49.

Whittaker, R.H. (1970). ***Communities and ecosystems.*** MacMillan, London, p 162.

Whittaker, R.H. (1974). Climax concepts and recognition. IN ***Knap, R. (Editor) Vegetation Dynamics.*** The Hague,p 137-154.

Yoda, K. et al (1963). Self-thinning in overcrowded pure conifer stands under cultivated and natural conditions. ***Journal of Biology Osaka City University 14,*** 107-129.

Zobel, B.J. and Buijtenen, J.P. van (1989). ***Wood variation, its causes and control.*** Springer-Verlag, Berlin etc. pp. 363.

APPENDIX 1. FORET COMMON BLOCKS, VARIABLES AND ARRAYS

adapted from : (Fricker 1988)

COMMON BLOCKS

Name	Bytes	Contents
FOREST	8580	Forest data
PARAM	780	Species parameters
CONST	12	Constant variables for plot
RAN	4	Uniform random number
RAN2	4	Normal random number
DEAD	5600	Information on tree growth
DEG	8	Mean, sd of DEGD
COUNT	8	No. of trees No. of years in simulation
TEMP	5600	Temporary diameters and ages
PLOT	30504	Start plot data
PASSX	19232	Biomass array for output
FREQ	21125	Diameter class frequency data

VARIABLES

Name	Type	Contents
AL	R*4	Available light
AM	R*4	Mean number of degree days for an area
AREA	R*4	Total leaf area
ATOT	R*4	Total number of trees
DEGD	R*4	Number of degree days for the year
DINC	R*4	Diameter increment (from growth equation and multipliers)
DMX	R*4	Maximum diameter
GR	R*4	DMX*HMX
HMX	R*4	Maximum height
HT	R*4	Height of individual tree
IHT	I*4	Height class
IPLOT	I*4	Plot number (simulation number)
KLAST	I*4	Number of simulations
KTIMES	I*4	Variable to allow for seed viability period (not in use)
KYR	I*4	Year
KYR1	I*4	KYR+1
MPLANT	I*4	Number of saplings regenerating
N1	I*4	NSPEC+1
N2	I*4	NSPEC+2
N3	I*4	NSPEC+3
NPLOTS	I*4	Number of plots from 1967 stand used as start plots
NSEED	I*4	Seeed for random number generation
NSP	I*4	Number of species for birth (inclusive)
NSPC	I*4	Number of species for sprouting (inclusive)
NSPEC	I*4	Number of species in the simulation
NSPRT	I*4	Number of sprouts
NSUM	I*4	Total nuber for birth or sprouting (inclusive)
NTOT	I*4	Toatal number of trees
NTR	I*4	Total number of trees in the start plot
NUM	I*4	Number to identify chosen species for simulation
NW	I*4	Number of species which can have saplings
NYEAR	I*4	Number of years in the simulation
NYR1	I*4	NYEAR+1
PHI	R*4	Annual insolation
PON	R*4	Leaf area exponent

RAL	R*4	Light attenuation growth multiplier
RAT	R*4	Random number
REDUCE	R*4	(SO_2 studies, not in use)
S	R*4	Standard deviation of degree-days
SBAR	R*4	Resource/space competiton growth-multiplier
SBIO	R*4	Total biomas of the stand
SENSIT	I*4	(SO_2 studies, not in use)
SIZE	R*4	Size of smallest sapling or sprout to be added to the plot
SLAR	R*4	Total leaf area above a tree
SOILQ	R*4	Maximum recorded biomass for a partivular forest type
TBAR	R*4	Total biomass
TDEGD	R*4	Temperature limits for species growth multiplier
X	R*4	Annual increment below which greater mortality applies mm
YFL	R*4	Random number
Z	R*4	Carries a normally distributed random number
ZNYR	R*4	KLAST

ARRAYS

Name	Type	Bytes	Dimensions	Contents
A	R*4	19232	(601,8)	Accumulated values for No trees, biomass leaf area
AAA	CHAR	100	(10)	Species names
AGEMX	R*4	40	(10)	Maximum species age
B1	R*4	40	(10)	Height-diameter coefficient
B2	R*4	40	(10)	Height-diameter coefficient
B3	R*4	40	(10)	Height-diameter coefficient
BAR	R*4	40	(10)	Biomass on plot
CURVE	R*4	40	(10)	(not in use)
D	R*4	15000	(150,25)	Diameters of start plot
DBH	R*4	2800	(700)	Diameters of trees
DMAX	R*4	40	(10)	Degree-day maximum
DMIN	R*4	40	(10)	Degree-day minimum
DTEMP	R*4	2800	(700)	Temporary diameter store
G	R*4	40	(10)	Species growth constant
IAGE	I*4	2800	(700)	Tree ages
IFREQ	I*4	260	(5,13)	Diameter frequency/year
ITEMP	I*4	2800	(700)	Temporary tree age store
ITOL	I*4	40	(10)	Tolerance to shade
JAGE	I*4	15000	(150,25)	Ages of start plot trees
JFREQ	I*4		(3006,5)	Sum of dbh frequencies
KSPRT	I*4	40	(10)	Species sprouting flag
KTIME	I*4	40	(10)	Time limit for spp intro
NEW	I*4	40	(10)	Species that can sprout
NEWTR	I*4	40	(10)	Species producing sapling
NOGRO	I*4	2800	(700)	Higher mortality flag .1 mm
NSELCT	I*4	40	(10)	Selected species for run
NT	I*4	500	(5,25)	No of trees in start plot
NTEMP	I*4	2800	(700)	Temporary NOGRO store
NTREES	I*4	40	(10)	No of trees by species
SPRTMN	R*4	40	(10)	Min dbh dead tree sprouts
SPRTMX	R*4	40	(10)	Max dbh dead tree sprouts
SPRTND	R*4	40	(10)	Max No of sprouts allowed
SUMLA	R*4	2800	(700)	Sum leaf area by ht class
SWITCH	L*4	200	(10,5)	Species regen switches
SWTCH	L*4	20	(5)	Site regen switches

APPENDIX 2. COMPLETE LISTING OF THE PROGRAM FORET

ALL ALTERATIONS MADE AS A RESULT OF THE AUTHORS WORK ARE EMBOLDENED.

```
      PROGRAM FORET
C
C*******This version of FORET has separate graphics and starts from the
C*******1967 stand,and does dbh file output correctly this version sums dbh frequency
C*******It uses a height equation, log(h-130)=b1+b2logD+b3(logd)^2
C*******It uses new growth equations
C*******It uses mortality to prevent biomass overestimation
C*******SOILQ - Meathop value for 1/12 hectare plot
C*******DEGD - from data collected at Merlewood  is ignored in the model
C*******Plot size is not 10x10m (far too small!) but now 1/12th ha
C*******Common statements
C
      COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
     . NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
      COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
     .ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
     .SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
      COMMON/CONST/NSPEC,SOILQ,DEGD
      COMMON/RAN/YFL
      COMMON/RAN2/Z
       COMMON/FREQ/JFREQ(3006,13)
      COMMON/DEAD/NOGRO(700),NTEMP(700)
      COMMON/DEG/AM,S
      COMMON/COUNT/NTOT,NYEAR
      COMMON/TEMP/DTEMP(700),ITEMP(700)
      COMMON/PLOT/D(150,100),JAGE(150,100),NT(5,100),NPLOTS
      COMMON/PASSX/A(601,8)
C*******
          CHARACTER*10 AAA
      LOGICAL SWITCH,SWTCH
C
C*******Seeds for random number generation
C
      NSEED = 70291
      NSEED = 71213
C
C*******Read in number of simulations.
C
      WRITE(6,601)
      READ(5,501) KLAST
      NPLOTS = KLAST
C*******
      CALL INPUT
      IPLOT = 0
      KTIMES = 1
      NYEAR = 600
      NYR1 = NYEAR+1
      N3 = NSPEC+3
C
C*******First call to random number generator to initialize further
C*******random number generation.
C
```

```
        X = RAND(NSEED)
C*******
        OPEN(UNIT=4,FILE='A.DAT',STATUS='NEW')
        OPEN(UNIT=7,FILE='DBH.OUT',STATUS='NEW')
C       OPEN(UNIT=9,FILE='FORET_NS2.OUT',STATUS='NEW')
C
C*******AM - Mean value for growing degree-days
C*******S  - Standard deviation for growing degree-days
C
C*******American value:
C       AM = 5858.
C       S = 655.98
C
C*******Meathop value:
C       AM = 2008.217
C       S = 51.546
C
C*******Merlewood value:
        AM = 2421.
        S = 179.66
C
C*******Morecombe value:
C       AM = 2927.
C       S = 188.27
C
C*******Initialize biomass array
C
        DO 10 IVA = 1,NYR1
                DO 10 IVS = 1,N3
                        A(IVA,IVS) = 0.
 10     CONTINUE
C
C*******SOILQ - The maximum biomass recorded for forests in the area
C
C*******SOILQ is in kg per 1/12 ha
C*******Amercican value:
C       SOILQ = 50833.33333
C*******Meathop value:
        SOILQ = 27291.66667
C
C*******SOILQ is in kg per 10m*10m plot.
C       SOILQ = 3275.
C
C*******DEGD - The growing degree-days for a site using a 42 deg F base
C
        DEGD = AM
C*******
 20     CONTINUE
        CALL PLOTIN(IPLOT)
C       WRITE(9,901) IPLOT
        WRITE(6,602) IPLOT
        KYR = 0
        CALL OUTPUT(KYR,IPLOT)
        DO 60 JJ = 1,KTIMES    !!!!!???????????????????????????????????
                CALL INIT
                DO 50 I = 1,NYEAR
                        KYR = I
C                       WRITE(9,902) KYR
```

```
                              CALL RNORM(NSEED)    !Calculate the number of
                                DEGD = Z           !degree-days for that year
                              CALL KILL
                              CALL BIRTH(KYR)
                              CALL GROW
                                  CALL OUTPUT(KYR,IPLOT)
50                  CONTINUE
60       CONTINUE
C
C*******Check to see if last simulation
C
         IF (IPLOT.NE.KLAST) GO TO 20
C
C*******Output averaged species biomass, total biomass, stems, leaf area
C*******to file to be used in graphics program(s)
C
         ZNYR = KLAST
         DO 80 IV1 = 1,NYR1
                  DO 70 IV2 = 1,N3
                           A(IV1,IV2) = A(IV1,IV2)/ZNYR
                           WRITE(4,401) A(IV1,IV2)
70                 CONTINUE
80       CONTINUE
C
C*******Produce output file containing DBH frequencies

         NF = 8
         DO 90 I=1,NSPEC
                  NL = I*601
                  IYEAR = 1
                     DO 100 J=NF,NL,20
                           DO 110 K=1,13
                           JFREQ(J,K) = JFREQ(J,K)
                                   WRITE(7,702) IYEAR,K,AAA(I),JFREQ(J,K)
110                        CONTINUE
                           IYEAR = IYEAR+20
100               CONTINUE
                  NF = NF+601
90       CONTINUE
C*******
         CLOSE(UNIT=4,STATUS='KEEP')
         CLOSE(UNIT=7,STATUS='KEEP')
C        CLOSE(UNIT=9,STATUS='KEEP')
C*******
         STOP
C
C*******Format statements
C
401   FORMAT(F10.5)
501      FORMAT(I4)
502      FORMAT(I7)
601      FORMAT(' Enter number of simulations')
602      FORMAT(/,'  PLOT NUMBER  ',I4)
C 701    FORMAT('SPECIES=',A10,
C   .             /'  YEAR 00-05 05-10 10-15 15-20 20-25 25-30 30-35 ',
C   .             '35-40 40-45 45-50 50-55 55-60 >=60')
702      FORMAT(I4,1X,I2,1X,A10,1X,I5)
901      FORMAT(/,'  PLOT NUMBER  ',I4)
```

```
902         FORMAT(' YEAR :',I4)
            END
C                                          C
C**********************************************************************C
C**********************************************************************C
C                                          C
            SUBROUTINE INPUT
            COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
   .        ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
   .        SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
             COMMON/CONST/NSPEC,SOILQ,DEGD
            COMMON/PLOT/D(150,100),JAGE(150,100),NT(5,100),NPLOTS
            INTEGER SENSIT
            CHARACTER*10 AAA
            LOGICAL SWITCH,SWTCH
            DIMENSION NSELCT(10)
C
C*******The variable reduce and the sensit array have been used in
C*******connection with SO2 studies.  The growth rate of individual
C*******species can be reduced according to SO2 sensitivity.
C*******
C*******NSPEC - Number of species
C*******NSELCT - Contains the species number for those species that will
C*******     be used in the simulation
C
      WRITE(6,601)
            READ(5,501) NSPEC,(NSELCT(I),I=1,NSPEC)
C           NSPEC = 5
C           DO 5 I=1,NSPEC
C                      NSELCT(I) = I
C 5         CONTINUE
            OPEN(UNIT=8,FILE='PARAM_MEATHOP.DAT',STATUS='OLD')
C*******
C*******Input individual species information
C*******AAA   - Species name
C*******DMAX  - Maximum growing degree-days
C*******DMIN  - Minimum growing degree-days
C*******B1-3  - Individual species height-diameter equation coefficients
C*******ITOL  - Light tolerance class
C*******AGEMX  - Maximum age of species
C*******CURVE  - Denotes type of curve for calculating biomass (not
C*******     currently used)
C*******G     - Scales the growth rate of each species
C*******GR    -Species maximum dimensions
C*******PON   - Leaf area exponent
C*******SPRTND - Tendancy to stump sprout
C*******SPRTMN - Minimum size dead tree that will sprout
C*******SPRTMX - Maximum size dead tree that will sprout
C*******SWITCH - Reproduction switches used in BIRTH
C*******KTIME  - Designates seed source limitation for certain species
C*******NUM   - Individual species number
C*******SENSIT - Denotes sensitivity to sulphur dioxide (not currently
C*******     used)
C
            J = 1
            REDUCE = 0.
            DO 10 K = 1,10
C                      WRITE(6,602)
```

```
C                    READ(8,801) AAA(J),DMAX(J),DMIN(J),B3(J),B2(J),ITOL(J),
C    .          AGEMX(J),CURVE(J),G(J),SPRTND(J),SPRTMN(J),
C    .                         SPRTMX(J),(SWITCH(J,I),I=1,5),KTIME(J),NUM,
C    .                              SENSIT
                     READ(8,801) AAA(J),DMAX(J),DMIN(J),B3(J),B2(J),B1(J),
     .         ITOL(J),AGEMX(J),G(J),PON(J),SPRTND(J),SPRTMN(J),
     .           SPRTMX(J),(SWITCH(J,I),I=1,5),KTIME(J),NUM,
     .        GR(J)
                     IF (NSELCT(J).NE.NUM) GO TO 10
                     IF (REDUCE.NE.0) G(J) = G(J)*(1.00-(SENSIT*REDUCE))
C                        WRITE(6,603) AAA(J),DMAX(J),DMIN(J),B3(J),B2(J),ITOL(J)
C    .                 ,AGEMX(J),CURVE(J),G(J),SPRTND(J),SPRTMN(J),
C    .                  SPRTMX(J),(SWITCH(J,I),I=1,5),KTIME(J),SENSIT,
C    .                         NUM
                     WRITE(6,603) AAA(J),DMAX(J),DMIN(J),B3(J),B2(J),B1(J),
     .           ITOL(J),AGEMX(J),G(J),PON(J),SPRTND(J),SPRTMN(J),
     .             SPRTMX(J),(SWITCH(J,I),I=1,5),KTIME(J),NUM
     .                   ,GR(J)
                     IF (NUM.EQ.NSELCT(NSPEC)) GO TO 20
                     J = J+1
 10          CONTINUE
 20          CONTINUE
             CLOSE(UNIT=8,STATUS=’KEEP’)
C
C*******Read in start plot data
C
             OPEN(UNIT=3,FILE=’PLOT2.DAT’,STATUS=’OLD’)
             DO 30 K=1,25
                     NTR = 0
                      READ(3,301) (NT(I,K),I=1,NSPEC)
                     DO 40 I=1,NSPEC
                             NTR = NTR + NT(I,K)
 40                  CONTINUE
                     IF (NTR.GT.150) WRITE(6,604)
                     DO 50 J=1,NTR
                             READ(3,302) D(J,K),JAGE(J,K)
 50                  CONTINUE
            DO 60 J=NTR+1,150
                             D(J,K) = 0.
                             JAGE(J,K) = 0
 60                  CONTINUE
 30          CONTINUE
             CLOSE(UNIT=3,STATUS=’KEEP’)
             RETURN
C
C*******Format statements
C
 301         FORMAT(5(I3,1X))
 302         FORMAT(F6.2,1X,I3)
 501         FORMAT(40I3)
 601         FORMAT(’ Enter number of species and the species numbers’)
 602         FORMAT(’ Entering parameters from data file’)
C 603        FORMAT(’ ’,A8,F6.0,1X,F5.0,1X,F4.3,1X,F5.2,1X,I1,1X,F4.0,1X,
C    .                F2.0,1X,F5.1,1X,F2.0,1X,F3.0,1X,F4.0,1X,5L1,1X,I2,1X,I2,
C    .               1X,I1)
C 801   FORMAT(A8,F5.0,1X,F4.0,1X,F4.3,1X,F5.2,1X,I1,1X,F3.0,1X,F1.0,1X,
C    .                F5.1,1X,F1.0,1X,F2.0,1X,F3.0,1X,5L1,1X,I2,1X,I2,1X,I1)
603   FORMAT(’ ’,A9,F4.0,1X,F4.0,1X,F6.4,1X,F5.3,1X,F5.3,1X,I1,1X,
```

```
     .       F3.0,1X,F4.0,1X,F6.3,1X,F1.0,1X,F2.0,1X,F3.0,5L1,1X,I2,
     .   I2,F6.0)
604       FORMAT(' Numbers of trees in start plot exceeds 150 ',
     .    '- redefine arrays!')
801   FORMAT(A9,F4.0,1X,F4.0,1X,F6.4,1X,F5.3,1X,F5.3,1X,I1,1X,F3.0,
     .       1X,F4.0,1X,F6.3,1X,F1.0,1X,F2.0,1X,F3.0,5L1,1X,I2,I2,
     .   F6.0)
          END
C                                                                      C
C**********************************************************************C
C**********************************************************************C
C                                                                      C
          SUBROUTINE PLOTIN(IPLOT)
          COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
     .     NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
          COMMON/CONST/NSPEC,SOILQ,DEGD
          COMMON/PLOT/D(150,100),JAGE(150,100),NT(5,100),NPLOTS
C
C*******Initialise variables to start simulation from 1967 stand
C*******NTREES contains number of trees for each species
C*******DBH contains diameter at breast height for each tree
C*******IAGE contains the age of each tree
C
          IPLOT = IPLOT+1
          DO 10 I = 1,NSPEC
                  NTREES(I) = NT(I,IPLOT)
                  DBH(I) = D(I,IPLOT)
                  IAGE(I) = JAGE(I,IPLOT)
 10       CONTINUE
          DO 20 I = NSPEC+1,150
                  DBH(I) = D(I,IPLOT)
                  IAGE(I) = JAGE(I,IPLOT)
 20        CONTINUE
          DO 30 I =150,700
                  DBH(I) = 0
                  IAGE(I) = 0
 30       CONTINUE
          RETURN
          END
C                                                                      C
C**********************************************************************C
C**********************************************************************C
C                                                                      C
          SUBROUTINE INIT
          COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
     .     NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
          COMMON/CONST/NSPEC,SOILQ,DEGD
          COMMON/DEAD/NOGRO(700),NTEMP(700)
C
C*******Initialise variables to zero for replicate plots
C
C*******KSPRT is used to flag the trees that can sprout
C*******NOGRO is used to flag the trees that do not grow
C
          DO 10 I = 1,NSPEC
                  NOGRO(I) = 0
                  KSPRT(I) = 1
 10       CONTINUE
```

```
         DO 20 I = NSPEC+1,700
                NOGRO(I) = 0
 20       CONTINUE
         RETURN
         END
C                                      C
C*************************************************************************C
C*************************************************************************C
C                                      C
         SUBROUTINE RANDOM
         COMMON/RAN/YFL
C
C*******SUBROUTINE RANDOM calls the uniform random number generator and
C*******returns the random number in YFL
C
         YFL = RAND(0)
         RETURN
         END
C                                      C
C*************************************************************************C
C*************************************************************************C
C                                      C
         SUBROUTINE KILL
         COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
    .      NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
         COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
    .    ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
    .    SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
         COMMON/CONST/NSPEC,SOILQ,DEGD
         COMMON/RAN/YFL
         COMMON/DEAD/NOGRO(700),NTEMP(700)
         COMMON/COUNT/NTOT,NYEAR
         CHARACTER*10 AAA
         LOGICAL SWITCH,SWTCH
         KNT = 0
          DO 30 I = 1,NSPEC
                IF (NTREES(I).EQ.0) GO TO 30
                NL = KNT+1
                NU = NTREES(I)+KNT
                DO 20 K = NL,NU
                       CALL RANDOM
C
C***********************Kill trees based on probability that only 1%
C***********************reach maximum age
C
                       IF (YFL.LE.(4.605/AGEMX(I))) GO TO 10
C
C***********************Kill trees on the basis that only 36.8% of the
C***********************trees growing less than 0.1mm in the last year
C***********************will survive.
C
                       IF (NOGRO(K).EQ.0) GO TO 20
                       CALL RANDOM
                        IF (YFL.LE.0.068) GO TO 20
 10                    CONTINUE
                       NTREES(I) = NTREES(I)-1
C
C***********************Check to see if dead tree can stump sprout.  Set
```

```
C***********************KSPRT to -1 if tree can sprout
C
                              IF (DBH(K).GT.SPRTMN(I).AND.DBH(K).LT.SPRTMX(I))
     .                          KSPRT(I) = -1
                              DBH(K) = -1.0
 20                 CONTINUE
                    KNT = NU
 30         CONTINUE
C
C*******Rewrite diameters and ages to eliminate dead trees
C
            K = 0
            DO 40 I = 1,700
                    IF (DBH(I).EQ.0.) GO TO 50
                    IF (DBH(I).LT.0.) GO TO 40
                    K = K+1
                    DBH(K) = DBH(I)
                    IAGE(K) = IAGE(I)
                    NOGRO(K) = NOGRO(I)
 40         CONTINUE
 50          NTOT = K
            IF (NTOT.EQ.0) RETURN
            DO 60 I = NTOT+1,NU
                      DBH(I) = 0.
                    IAGE(I) = 0
                    NOGRO(I) = 0
 60         CONTINUE
            RETURN
            END
C                                     C
C*********************************************************************C
C*********************************************************************C
C                                     C
            SUBROUTINE SPROUT
            COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
     .       NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
            COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
     .      ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
     .      SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
            COMMON/CONST/NSPEC,SOILQ,DEGD
            COMMON/RAN/YFL
            COMMON/DEAD/NOGRO(700),NTEMP(700)
            COMMON/COUNT/NTOT,NYEAR
            COMMON/TEMP/DTEMP(700),ITEMP(700)
            CHARACTER*10 AAA
            LOGICAL SWITCH,SWTCH
C
C*******Smallest average stump sprout is 0.1 cm
C
            SIZE = .1
C
C*******Sum total number of trees
C
            NTOT = 0
            DO 10 I = 1,NSPEC
                    IF (NTREES(I).EQ.0) GO TO 10
                    NTOT = NTOT+NTREES(I)
 10          CONTINUE
```

```
C
C*******Determine which species can sprout
C
          NW = 0
          DO 20 I = 1,NSPEC
                     IF (SPRTND(I).LE.0) GO TO 20
                    IF (KSPRT(I).GE.0) GO TO 20
                    NW = NW+1
                    NEW(NW) = I
 20       CONTINUE
C
C*******Check for sprouts
C
          IF (NW.EQ.0) GO TO 90
          DO 30 J = 1,NTOT
                    ITEMP(J) = IAGE(J)
                    DTEMP(J) = DBH(J)
                    NTEMP(J) = NOGRO(J)
 30       CONTINUE
C
C*******Select species to sprout
C
          CALL RANDOM
          NW = NW*YFL+1.0
          NSPC = NEW(NW)
C*******
          NSUM = 0
          DO 40 I = 1,NSPC
 40                 NSUM = NSUM+NTREES(I)
C
C*******SPRTND is the tendancy for the Ith species to stump or root
C*******sprout.  The value of SPRTND is the average number of sprouts
C*******that might occur with a tree death
C
C*******Randomly select number of trees to sprout
C
          CALL RANDOM
          NSPRT = YFL*SPRTND(NSPC)+1
C*******
          NL = NSUM+1
          NUP = NTOT
          DO 50 I = 1,NSPRT
                    NSUM = NSUM+1
                    NTREES(NSPC) = NTREES(NSPC)+1
                    NTOT = NTOT+1
                    IF (NTOT.GT.700) CALL ERR
                    ITEMP(NSUM) = 0
                    CALL RANDOM
                    DTEMP(NSUM) = SIZE+.1*(1.0-YFL)**3
                    NTEMP(NSUM) = 0
 50        CONTINUE
C
C*******Store diameters and ages for new sprouts
C
          IF (NL.GT.NUP) GO TO 70
          N1 = NSUM+1
          DO 60 J = NL,NUP
                    DTEMP(N1) = DBH(J)
```

```
                  ITEMP(N1) = IAGE(J)
                  NTEMP(N1) = NOGRO(J)
                  N1 = N1+1
 60       CONTINUE
C
C*******Reinitialise original diameters and ages
C
 70       DO 80 L = 1,NTOT
                  IAGE(L) = ITEMP(L)
                  NOGRO(L) = NTEMP(L)
 80               DBH(L) = DTEMP(L)
 90       CONTINUE
C
C*******Reinitialise sprout switch for each species
C
          DO 100 I = 1,NSPEC
 100              KSPRT(I) = 1
          RETURN
          END
C                                                  C
C**********************************************************************C
C**********************************************************************C
C                                                  C
          SUBROUTINE GROW
          COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
     .      NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
          COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
     .    ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
     .    SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
          COMMON/CONST/NSPEC,SOILQ,DEGD
          COMMON/RAN/YFL
          COMMON/DEAD/NOGRO(700),NTEMP(700)
          COMMON/COUNT/NTOT,NYEAR
          COMMON/TEMP/DTEMP(700),ITEMP(700)
          CHARACTER*10 AAA
          LOGICAL SWITCH,SWTCH
C
C*******DBH is in centimetres
C*******Each tree is required to add a 1mm growth ring each year
C
          TINC = .09
C*******
          PHI = 1.
C
C*******Calculate total number of trees
C
          NTOT = 0
          DO 10 I = 1,NSPEC
 10               NTOT = NTOT+NTREES(I)
          IF (NTOT.EQ.0) RETURN
C
C*******Sum leaf area of all trees that are of approximately the same
C*******height
C
          DO 20 I = 1,700
                  NOGRO(I) = 0
 20               SUMLA(I) = 0.
          NL = 1
```

```
          SBIO = 0.
          DO 40 J = 1,NSPEC
                    IF (NTREES(J).EQ.0) GO TO 40
                    NU = NL+NTREES(J)-1
                    DO 30 K = NL,NU
C
C***********************Calculate stand biomass
C
                              SBIO = SBIO+.1193*DBH(K)**2.393
C
C***********************Height profile is calculated in .1 metre units
                              IHT = (130.+10**(B1(J)+(B2(J)*ALOG(DBH(K))
     .           )-(B3(J)*(ALOG(DBH(K)))**2)))/(10.+1.)
                              IF (IHT.GT.700) GO TO 90
                                  SUMLA(IHT) = SUMLA(IHT)+1.9283295E-4
     .                             *DBH(K)**2.129
 30                 CONTINUE
                    NL = NL+NTREES(J)
 40       CONTINUE
           DO 50 J = 1,699
                    J1 = 700-J
                    SUMLA(J1) =SUMLA(J1)+SUMLA(J1+1)
 50       CONTINUE
C
C*******Calculate amount of growth for each tree
C
          NL = 1
          DO 80 I = 1,NSPEC
                    IF (NTREES(I).EQ.0) GO TO 80
                    NU = NL+NTREES(I)-1
                    DO 70 J = NL,NU
              HT = 130.+ 10**(B1(I)+(B2(I)*ALOG10(DBH(J)))
     .        - (B3(I) * (ALOG10(DBH(J)))**2))
                              IHT = HT/10.+2.
                              SLAR = SUMLA(IHT)
C
C***********************Calculate the available light.  The different
C***********************values of k are due to difference in plot size.
C
                              AL = PHI*EXP(-SLAR*.25)
C                              AL = PHI*EXP(-SLAR*(1/6000))
C
C***********************The commented lines are the original equations
C***********************based on H=137+b2*D-b3*D**2
C
C                             HMX = 137.+.25*B2(I)**2/B3(I)
C                             DMX = 0.5*B2(I)/B3(I)
C                             HMX = .25*B2(I)**2/B3(I)
C                              GR = HMX*DMX
C                             TDEGD = 4.0*(DEGD-DMIN(I))*(DMAX(I)-DEGD)
C    .                                  /(DMAX(I)-DMIN(I))**2
C                             OBAR = 1.0-(SBIO/SOILQ)
                              SBAR = 1.0-((SBIO/SOILQ)*(1.0-((DBH(J)*(
     .               130.+10.**(B1(I)+B2(I)*ALOG10(DBH(J)))-
     .               (B3(I)*(ALOG10(DBH(J)))**2)))/GR(I))))
                              RAL = 2.24*(1.-EXP(-1.136*(AL-.08)))
                              IF (ITOL(I).LT.2) RAL = (1.0-EXP(-4.64*(AL-.05)
     .                        ))
```

```
                            TDEGD = 1
                DINC = G(I)*(DBH(J)**PON(I))*(1-((DBH(J)*(((10**B1
   .                 (I))*(DBH(J)**(B2(I)-(B3(I)*ALOG10(DBH(J)
   .                 ))))))/(GR(I))))/((260.+(10**B1(I))*(DBH(
   .                 J)**(B2(I)-(B3(I)*(ALOG10(DBH(J)))))))*(2
   .                 +B2(I)-(B3(I)*(ALOG10(DBH(J))))))*RAL*
   .                 TDEGD*SBAR
C                           DINC = G(I)*DBH(J)*(1.0-(137.*DBH(J)+B2(I)
C    .                         *DBH(J)**2-B3(I)*DBH(J)**3)/GR)/
C    .                       (274.+3.0*B2(I)*DBH(J)-4.0*B3(I)*DBH(J)
C    .                       **2)*RAL*TDEGD*SBAR
C
C***********************Check increment less than TINC required growth
C
                IF (((SBIO/SOILQ).GT.0.9).AND.(((DBH(J)*HT)/GR(I
   .                        )).GT.0.5)) DINC = 0.0
                        IF (DINC.LT.TINC) DINC = 0.0
                            IF (DINC.NE.0.) GO TO 60
                            NOGRO(J) = -1
 60                         DBH(J) = DBH(J)+DINC
 70                 CONTINUE
                    NL = NL+NTREES(I)
 80         CONTINUE
            RETURN
 90         WRITE(6,601)
            STOP
 601        FORMAT('1 IHT EXCEEDED 700')
            END
C                                       C
C***********************************************************************C
C***********************************************************************C
C                                       C
            SUBROUTINE BIRTH(KYR)
            COMMON/FOREST/NTREES(10),DBH(700),IAGE(700),KSPRT(10),
   .          NEWTR(10),SUMLA(700),NEW(10),SWTCH(5)
            COMMON/PARAM/AAA(10),DMAX(10),DMIN(10),B3(10),B2(10),B1(10),
   .        ITOL(10),AGEMX(10),CURVE(10),G(10),PON(10),SPRTND(10),
   .        SPRTMN(10),SPRTMX(10),SWITCH(10,5),KTIME(10),GR(10)
            COMMON/CONST/NSPEC,SOILQ,DEGD
            COMMON/RAN/YFL
            COMMON/DEAD/NOGRO(700),NTEMP(700)
            COMMON/DEG/AM,S
            COMMON/COUNT/NTOT,NYEAR
            COMMON/TEMP/DTEMP(700),ITEMP(700)
             CHARACTER*10 AAA
            LOGICAL SWITCH,SWTCH
C
C*******Saplings enter the plot at average size of 1.27cm DBH
C
            SIZE = 1.27
C
C*******Select a species from 1 to 3 times
C
            CALL RANDOM
            NPLANT = 3.*YFL+1
C*******RAT random number is fixed for year - used in SWITCH 4
C
            CALL RANDOM
```

```
          RAT = YFL
          DO 140 JK = 1,NPLANT
 10               AREA = 0.
                    NL = 1
C
C***************Calculate leaf area for each species
C
                  DO 30 J = 1,NSPEC
                        IF (NTREES(J).EQ.0) GO TO 30
                        NU = NL+NTREES(J)-1
                           DO 20 K = NL,NU
                                 AREA = AREA+1.9283295E-4*DBH(K)**2.129
 20                       CONTINUE
                        NL = NL+NTREES(J)
 30                CONTINUE
C
C***************Total number of trees in stand
C
                  NTOT = NL-1
C
C***************SWITCH 1 is true if: the species requires leaf litter
C***************        for successful recruitment
C***************SWITCH 2 is true if: the species requires mineral soil
C***************SWITCH 3 is true if: the species recruitment is reduced
C***************         by hot year
C***************SWITCH 4 is true if: the species is a preferred food of
C***************               small mammals
C***************SWITCH 5 reduces seeding rate of desirable mast
C
                 DO 40 J = 1,5
                        SWTCH(J) = .TRUE.
 40                CONTINUE
C
C***************Set switches based on value of biomass, DEGD, and random
C***************number
C
                  IF (AREA.GE..1) SWTCH(1) = .FALSE.
                 IF (AREA.LE..15) SWTCH(2) = .FALSE.
                 IF (DEGD.LE.AM) SWTCH(3) = .FALSE.
                 IF (RAT.GT..5) SWTCH(4) = .FALSE.
                 CALL RANDOM
                 IF (YFL.GE..5) SWTCH(5) = .FALSE.
C
C***************Check switches to determine if seeding is allowed
C
                  NW = 0
                 DO 60 J = 1,NSPEC
                        DO 50 K = 1,5
                               IF (SWITCH(J,K).AND.SWTCH(K)) GO TO 60
 50                     CONTINUE
                        IF (KTIME(J).NE.0.AND.KYR.GT.KTIME(J).AND.
  .                               NTREES(J).LE.0) GO TO 60
                        NW = NW+1
                        NEWTR(NW) = J
 60              CONTINUE
C
C***************Check to see if there are any new trees
C
```

```
        RAT = YFL
        DO 140 JK = 1,NPLANT
 10             AREA = 0.
                    NL = 1
C
C***************Calculate leaf area for each species
C
                 DO 30 J = 1,NSPEC
                         IF (NTREES(J).EQ.0) GO TO 30
                         NU = NL+NTREES(J)-1
                            DO 20 K = NL,NU
                                   AREA = AREA+1.9283295E-4*DBH(K)**2.129
 20                        CONTINUE
                         NL = NL+NTREES(J)
 30               CONTINUE
C
C***************Total number of trees in stand
C
                 NTOT = NL-1
C
C***************SWITCH 1 is true if: the species requires leaf litter
C***************            for successful recruitment
C***************SWITCH 2 is true if: the species requires mineral soil
C***************SWITCH 3 is true if: the species recruitment is reduced
C***************             by hot year
C***************SWITCH 4 is true if: the species is a preferred food of
C***************                    small mammals
C***************SWITCH 5 reduces seeding rate of desirable mast
C
                 DO 40 J = 1,5
                         SWTCH(J) = .TRUE.
 40               CONTINUE
C
C***************Set switches based on value of biomass, DEGD, and random
C***************number
C
                 IF (AREA.GE..1) SWTCH(1) = .FALSE.
                 IF (AREA.LE..15) SWTCH(2) = .FALSE.
                 IF (DEGD.LE.AM) SWTCH(3) = .FALSE.
                 IF (RAT.GT..5) SWTCH(4) = .FALSE.
                 CALL RANDOM
                 IF (YFL.GE..5) SWTCH(5) = .FALSE.
C
C***************Check switches to determine if seeding is allowed
C
                 NW = 0
                 DO 60 J = 1,NSPEC
                         DO 50 K = 1,5
                                 IF (SWITCH(J,K).AND.SWTCH(K)) GO TO 60
 50                      CONTINUE
                         IF (KTIME(J).NE.0.AND.KYR.GT.KTIME(J).AND.
     .                                NTREES(J).LE.0) GO TO 60
                         NW = NW+1
                         NEWTR(NW) = J
 60              CONTINUE
C
C***************Check to see if there are any new trees
C
```

```
            IF (NW.EQ.0) GO TO 130
C
C***************Calculate age and diameter for new trees
C
            DO 70 I = 1,NTOT
                  ITEMP(I) = IAGE(I)
                  DTEMP(I) = DBH(I)
                  NTEMP(I) = NOGRO(I)
 70         CONTINUE
C
C***************Determine the number of seedlings to plant 0 to 7
C
            CALL RANDOM
            MPLANT = 8.*YFL
C
C***************Select seedlings (particular species)
C
            CALL RANDOM
            NW = NW*YFL+1.0
            NSP = NEWTR(NW)
            NSUM = 0
            DO 80 I =1,NSP
 80               NSUM = NSUM+NTREES(I)
C
C***************Plant random number of seedlings
C
            NL = NSUM+1
            NUP = NTOT
            DO 90 J = 1,MPLANT
                  NTOT = NTOT+1
                  IF (NTOT.GT.700) CALL ERR
                  NSUM = NSUM+1
                  NTREES(NSP) = NTREES(NSP)+1
                  ITEMP(NSUM) = 0
                  CALL RANDOM
                  DTEMP(NSUM) = SIZE+.3*(1.0-YFL)**3
                  NTEMP(NSUM) = 0
 90         CONTINUE
            IF (NL.GT.NUP) GO TO 110
            N1 = NSUM+1
            DO 100 L = NL,NUP
                  DTEMP(N1) = DBH(L)
                  ITEMP(N1) = IAGE(L)
                  NTEMP(N1) = NOGRO(L)
                  N1 = N1+1
 100        CONTINUE
C
C***************Reinitialise original DBH and age arrays - including new
C***************trees
C
 110        DO 120 I = 1,NTOT
                  IAGE(I) = ITEMP(I)
                  DBH(I) = DTEMP(I)
                  NOGRO(I) = NTEMP(I)
 120        CONTINUE
 130        CONTINUE
C           CALL SPROUT
            IF (NW.NE.0.AND.AREA.LT.0.15) GO TO 10
```

```
                   NL = NU+1
                NTOT = NTOT+NTREES(I)
 20     CONTINUE
C
C*******Add this simulation's diameter frequencies for this year
C*******to "permanent" frequency array

        K=KYR1
        DO 23 I=1,NSPEC
                      DO 25 J=1,13
                             JFREQ(K,J) = JFREQ(K,J)+IFREQ(I,J)
 25                       CONTINUE
                      K = K+600
 23     CONTINUE
C
C*******J.C.L. changes must be made to use the following write statement
C
        TBAR = TBAR*.012
C       TBAR = TBAR*.1
        DO 30 IV1 = 1,NSPEC
                BAR(IV1) = BAR(IV1)*.012
C               BAR(IV1) = BAR(IV1)*.1
                A(KYR1,IV1) = A(KYR1,IV1)+BAR(IV1)
 30     CONTINUE
        ATOT = NTOT
        N1 = NSPEC+1
        N2 = N1+1
        N3 = N2+1
        A(KYR1,N1) = A(KYR1,N1)+TBAR
        A(KYR1,N2) = A(KYR1,N2)+ATOT
        A(KYR1,N3) = A(KYR1,N3)+AREA
C
C*******Output number of trees and biomass for each species and the
C*******total biomass, total number of trees, total leaf area every 50
C*******years.
C
C        IF (MOD(KYR,50).EQ.0) THEN
C       IF (KYR.LE.50) THEN
C                  WRITE(9,901) KYR
C               DO 40 I=1,NSPEC,5
C                      WRITE(9,902) (J,J=I,I+4),(NTREES(J),J=I,I+4),
C    .                    (BAR(J),J=I,I+4)
C 40            CONTINUE
C               WRITE(9,903) TBAR,NTOT,AREA
C       ENDIF
C
C*******Format statements
C
 901    FORMAT(' YEAR = ',I3/)
 902    FORMAT(' SPECIES :',5(1X,I10),/' NTREES  :',5(1X,I10),
   .            /' BAR     :',5(1X,F10.6)/)
 903  FORMAT(' TBAR :',F11.6,6X,'ATOT :',I4,6X,'AREA :',F10.6,
   .            /'****************************************************',
   .            '****************')
        RETURN
        END
C                                C
C*******************************************************************C
```

```
C******************************************************************************C
C                                                         C
          SUBROUTINE ERR
          WRITE(6,901)
          STOP
 901      FORMAT('1 THE NUMBER OF TREES HAS EXCEEDED 700')
          END
C                                                         C
C******************************************************************************C
C******************************************************************************C
C                                                         C
          SUBROUTINE RNORM(NSEED)
          COMMON/DEG/AM,S
          COMMON/RAN2/Z
C
C*******Calculates normally distributed random numbers
C
          Z = RANDN(AM,S)
          RETURN
          END
```

APPENDIX 3. PROGRAM LISTINGS FOR THE ECONOMICS MODEL

MENU PROGRAM AND DECISIONS PROGRAM WERE WRITTEN ENTIRELY BY THE AUTHOR.

PROGRAM MEN2 (MENU PROGRAM)

```
10 KEY OFF:CLS:FOR X%=1 TO 10:KEY X%,"":KEY(X%) ON:NEXT X%
12 PRINT:PRINT"   WOODMAN III                  5, inch version          JANUARY 1989
"
14 PRINT:PRINT"   M.J. Spilsbury, Oxford Forestry Institue, South Parks Rd, Oxford
OX1 3RB"
15 PRINT:PRINT TAB(13) "This program is designed to  help owners choose suitable"
16 PRINT TAB(13) "silvicultural regimes for their woodlands. It calculates"
17 PRINT TAB(13) "Land Expectation Values (LEV's)  in 's for a wide range"
18 PRINT TAB(13) "of management alternatives. Adjustments to LEV's  can be"
19 PRINT TAB(13) "made according to the particular circumstances, in terms"
20 PRINT TAB(13) "of likely costs/revenues and grants available. The LEV's"
21 PRINT TAB(13) "derived give a guide to  the relative profitabilities of"
22 PRINT TAB(13) "different options.  They  are intended  to  be used  for"
23 PRINT TAB(13) "making comparisons between  possible initial choices and"
24 PRINT TAB(13) "NOT for providing absolute values."
25 PRINT:PRINT TAB(33)"PRESS ANY KEY":PRINT:PRINT TAB(13) "This work was
financed by the Energy Technology Division"
26 PRINT TAB(13) "of the Atomic Energy  Research  Establishment  under the"
27 PRINT TAB(13) "agreement E/5A/CON/1156/1166."
30 LOCATE 1,1:PRINT CHR$(201);:FOR X%=1 TO 78:PRINT CHR$(205);:NEXT
X%:PRINT CHR$(187);
31 FOR X%=2 TO 22:FOR Y%=1 TO 80 STEP 79:LOCATE X%,Y%,0:PRINT
CHR$(186):NEXT:NEXT
32 LOCATE 3,1:PRINT CHR$(199);:FOR X%=1 TO 78:PRINT CHR$(196);:NEXT
X%:PRINT CHR$(182);
33 LOCATE 18,1:PRINT CHR$(199);:FOR X%=1 TO 78:PRINT CHR$(196);:NEXT
X%:PRINT CHR$(182);
34 LOCATE 23,1:PRINT CHR$(200);:FOR X%=1 TO 78:PRINT CHR$(205);:NEXT
X%:PRINT CHR$(188);
60 ANS$=INKEY$:IF ANS$="" THEN GOTO 60
65 IF LEN(ANS$)>1 THEN GOTO 60
67 DIM KEV(19,2),KEV$(19)
70 CLS
80 PRINT:PRINT:PRINT"  (A) Plant with Douglas fir.                  HIGH INTENSITY
OPTIONS"
90 PRINT"  (B) Plant with Corsican pine."
100 PRINT"  (C) Plant with Japanese larch."
110 PRINT"  (D) Plant with Sitka spruce."
130 PRINT:PRINT"  (E) Plant with Douglas fir / Oak mixture.      MEDIUM INTENSITY
OPTIONS"
140 PRINT"  (F) Plant with Oak."
150 PRINT"  (G) Plant with Corsican pine / Beech mixture."
160 PRINT"  (H) Plant with Beech."
170 PRINT"  (I) Plant with Oak / Ash / Cherry."
180 PRINT"  (J) 30 year conversion to Oak / Ash / Cherry plantation."
190 PRINT"  (K) Underplant neglected woodland with Western red cedar."
200 PRINT"  (L) Convert neglected coppice to coppice-with-standards."
220 PRINT:PRINT"  (M) Re-coppice neglected Oak coppice (normalised age) LOW
INTENSITY OPTIONS"
230 PRINT"  (N) Re-coppice neglected Oak coppice (immediate conversion)."
```

```
240 PRINT"  (O) Plant simple coppice."
250 PRINT"  (P) Re-coppice neglected woodland of pure or mixed coppice species."
260 PRINT"  (Q) Convert neglected woodland to an Oak / Ash group system."
270 PRINT"  (R) Shelterwood system for Ash / Sycamore."
280 PRINT"  (S) Beech natural regeneration supplemented with native hardwood
whips."
290 PRINT"  (T) Birch natural regeneration.";TAB(44)"PRESS LETTER TO SELECT"
295 LOCATE 1,1:PRINT CHR$(201);:FOR X%=1 TO 78:PRINT CHR$(205);:NEXT
X%:PRINT CHR$(187)
296 FOR X%=2 TO 23:FOR Y%=1 TO 80 STEP 79:LOCATE X%,Y%,0:PRINT
CHR$(186);:NEXT Y%:NEXT X%
297 LOCATE 24,1:PRINT CHR$(200);:FOR X%=1 TO 78:PRINT CHR$(205);:NEXT
X%:PRINT CHR$(188);
300 LOCATE 6,1:PRINT CHR$(199);:FOR X%=1 TO 78:PRINT CHR$(196);:NEXT
X%:PRINT CHR$(182);
302 LOCATE 15,1:PRINT CHR$(199);:FOR X%=1 TO 78:PRINT CHR$(196);:NEXT
X%:PRINT CHR$(182);:LOCATE 1,1
350 A%=6
360 WHILE A%<>0
370 ANS$=INKEY$:IF ANS$="" THEN GOTO 370
375 IF LEN(ANS$)>1 THEN GOTO 370
380 A%=ASC(ANS$)
400 IF A%>96 AND A%<117 THEN A%=0
405 IF A%>64 AND A%<85 THEN A%=0
410 WEND
420 IF ANS$="A" OR ANS$="a" THEN PATH$= "A:\ETSU\DFIR":BR%= 12:GRANT$=
"A:\ETSU\COPL":EXT$=".WGS":OPT$="Douglas Fir.":COP%= 2 :FW%=184:BW%= 45
:FAWS%=20
430 IF ANS$="B" OR ANS$="b" THEN PATH$="A:\ETSU\CPINE":BR%=12:GRANT$=
"A:\ETSU\COPL": EXT$ =".WGS":OPT$="Corsican Pine.":COP%=2:FW% =178:BW%=
53:FAWS%=20
440 IF ANS$="C" OR ANS$="c" THEN PATH$="A:\ETSU\JL":BR%=11:GRANT$=
"A:\ETSU\COPL":EXT$=".WGS":OPT$="Japanese Larch.":COP%=2:FW%=86:
BW%=69:FAWS%=20
450 IF ANS$="D" OR ANS$="d" THEN PATH$="A:\ETSU\SSPRUCE":BR%=15:
GRANT$= "A:\ETSU\COPL":EXT$=".WGS":OPT$="Sitka Spruce.":COP%=2:
FW%=171 : BW%=56:FAWS%=20
460 IF ANS$="E" OR ANS$="e" THEN PATH$="A:\ETSU\DFOK":BR%=25:GRANT$=
"A:\ETSU\MCHP":EXT$=".WGS":OPT$="Douglas Fir / Oak.":COP%=0:FW%=282
:BW%=85:FAWS%=30

470 IF ANS$="F" OR ANS$="f" THEN PATH$="A:\ETSU\OAK":BR%=35:GRANT$=
"A:\ETSU\BWPL":EXT$=".WGS":OPT$="Oak.":COP%=0:FW%=265:BW%=74:FAWS%=40
480 IF ANS$="G" OR ANS$="g" THEN PATH$="A:\ETSU\BECP":BR%=25:GRANT$=
"A:\ETSU\MCHP":EXT$=".WGS":OPT$="Beech / Corsican Pine.":COP%=0:FW%=261
:BW%=82:FAWS%=30
490 IF ANS$="H" OR ANS$="h" THEN PATH$="A:\ETSU\BEECH":BR%=45:GRANT$=
"A:\ETSU\BWPL":EXT$=".WGS":OPT$="Beech.":COP%=0:FW%=265:BW%=74:FAWS%=40
500 IF ANS$="I" OR ANS$="i" THEN PATH$="A:\ETSU\OACH":BR%=40:GRANT$=
"A:\ETSU\BWPL":EXT$=".WGS":OPT$="Oak / Ash / Cherry.":COP%=0:FW%=285
:BW%=86:FAWS%=30
510 IF ANS$="J" OR ANS$="j" THEN PATH$="A:\ETSU\OACH30":BR%=40:GRANT$=
"A:\ETSU\BWPL":EXT$=".WGS":OPT$="30 year Oak / Ash / Cherry.":COP%=0
:FW%=285:BW%=86:FAWS%=30
520 IF ANS$="L" OR ANS$="l" THEN PATH$="A:\ETSU\ADJCWS":BR%=35: GRANT$
="A:\ETSU\BWPL":EXT$=".WGS":OPT$="Convert to coppice with standards"
:COP%=6:FW%=140:BW%=88:FAWS%=10
530 IF ANS$="K" OR ANS$="k" THEN PATH$="A:\ETSU\WRC":BR%=18:GRANT$=
```

```
"A:\ETSU\COPL":EXT$=".WGS":OPT$="Western Red Cedar under coppice.":COP%=2
:FW%=261:BW%=55:FAWS%=20
540 IF ANS$="M" OR ANS$="m" THEN PATH$="A:\ETSU\CNVOCOP":BR%=30:OPT$
="Oak coppice (normalised age).":COP%=8:FW%=175:BW%=77
550 IF ANS$="N" OR ANS$="n" THEN PATH$="A:\ETSU\OKCOP":BR%=30:OPT$=
"Even aged Oak coppice.":COP%=8:FW%=175:BW%=77
560 IF ANS$="Q" OR ANS$="q" THEN
PATH$="A:\ETSU\OAGRP30":BR%=42:GRANT$ ="A:\ETSU\OAGR3":EXT$=".BWG"
:OPT$="Oak / Ash group system from coppice.":COP%=7:FW%=326:BW%=59
:FAWS%=30
570 IF ANS$="S" OR ANS$="s" THEN PATH$="A:\ETSU\BENR":BR%=40:GRANT$=
"A:\ETSU\BWNR":EXT$=".WGS":OPT$="Beech by natural regeneration.":COP%=0
:FW%=265:BW%=74:FAWS%=40
580 IF ANS$="O" OR ANS$="o" THEN PATH$="A:\ETSU\COPLADJ":BR%=30:
GRANT$="A:\ETSU\BWPL":EXT$=".WGS":OPT$="Planting simple coppice.":COP%=9
:FW%=143:BW%=77:FAWS%=10
590 IF ANS$="P" OR ANS$="p" THEN PATH$="A:\ETSU\COP":BR%=30:OPT$=
"Convert to coppice.":COP%=8:FW%=143:BW%=77
600 IF ANS$="T" OR ANS$="t" THEN PATH$="A:\ETSU\BINR":BR%=20:GRANT$=
"A:\ETSU\BWNR":EXT$=".WGS":OPT$="Birch natural regeneration.":COP%=0
:FW%=137:BW%=39:FAWS%=30
610 IF ANS$="R" OR ANS$="r" THEN PATH$="A:\ETSU\ASYSH":BR%=42:GRANT$=
"A:\ETSU\BWNR":EXT$=".WGS":OPT$="Ash / Sycamore shelterwood.":COP%=0
:FW%=159:BW%=100:FAWS%=30
620 CLS:PRINT OPT$:PRINT TAB(15)"CASH FLOW FOR MEDIUM YIELD, PRICES,
GRANTS & 3% DISC RATE":PRINT"OPERATION";TAB(20)"YEAR";TAB(27)"VOLUME
cu.m";TAB(40)"PRICE ";TAB(50)"VALUE ";TAB(59)"CUM VAL ";TAB(70) "DISC VAL "
630 OPEN "R",#1,PATH$+".CF",4
640 FIELD #1,4 AS FILE$
650 FOR A=0 TO 19
660 FOR B=0 TO 2
670 GET#1
680 KEV(A,B)=CVS(FILE$)
690 NEXT B:NEXT A
700 CLOSE#1
800 OPEN "R",#1,PATH$+".NA",15
810 FIELD #1,15 AS FILE$
820 FOR A=0 TO 19
830 GET#1
840 KEV$(A)=FILE$
850 NEXT A
860 CLOSE#1
870 FOR A=0 TO 19
875 IF KEV(A,0)=0 AND KEV(A,1)=0 AND KEV(A,2)=0 THEN A=19:GOTO 890
878 IF KEV(A,1)=1 THEN PRINT KEV$(A);TAB(20) KEV(A,0);TAB(30) "
-";TAB(40)KEV(A,2);TAB(50)INT(KEV(A,1)*KEV(A,2));:CUML%=CUML%+
INT(KEV(A,1)*KEV(A,2)):PRINT TAB(60)CUML%;TAB(71)
INT(1/(1.03)^KEV(A,0)*KEV(A,1)*KEV(A,2)):GOTO 890
880 PRINT KEV$(A);TAB(20) KEV(A,0);TAB(30) KEV(A,1);TAB(40)KEV(A,2);TAB(50)
INT(KEV(A,1)*KEV(A,2));:CUML%=CUML%+INT(KEV(A,1)*KEV(A,2)):PRINT
TAB(60)CUML%;TAB(71)INT(1/(1.03)^KEV(A,0)*KEV(A,1)*KEV(A,2))
890 NEXT A:CUML%=0
895 LOCATE 24,1:PRINT "Estimated fuel-wood yield is ";FW%;"cu.m/ha/rotation  for
medium  yield  class.";
900 LOCATE 25,1:PRINT "Of this";BW%;"% is from branchwood."TAB(65)"PRESS
ANY KEY";:ANS$=INPUT$(1)
905 IF ANS$="X" OR ANS$="x" THEN CLS:GOTO 70 ELSE CLS
910 COMMON PATH$,GRANT$,BR%,EXT$,OPT$,COP%,FAWS%,KEV$(),KEV()
```

```
920 CHAIN"A:\ETSU\PHIL"
```

PROGRAM PHIL (DECISIONS PROGRAM)

```
5 FOR X%=1 TO 10:KEY X%,"":KEY (X%) ON:NEXT X%
14 CLS
15 LOCATE 2,45:PRINT OPT$
20 DIM LEV(14,4),YR(2,1),VO(2,4),CS(2,4),GR(4)
40 OPEN "R",#1,PATH$,4
50 FIELD #1,4 AS FILE$
60 FOR A%=0 TO 14
70 FOR B%=0 TO 4
80 GET #1
90 LEV(A%,B%)=CVS(FILE$)
100 NEXT B%:NEXT A%
110 CLOSE #1
130 OPEN "R",#1,PATH$+".YRS",4
140 FIELD #1,4 AS FILE$
150 FOR A%=0 TO 2
160 FOR B%=0 TO 1
170 GET #1
180 YR(A%,B%)=CVS(FILE$)
190 NEXT B%:NEXT A%
200 CLOSE #1
220 OPEN "R",#1,PATH$+".VOL",4
230 FIELD #1,4 AS FILE$
240 FOR A%=0 TO 2
250 FOR B%=0 TO 4
260 GET #1
270 VO(A%,B%)=CVS(FILE$)
280 NEXT B%:NEXT A%
290 CLOSE #1
310 OPEN "R",#1,PATH$+".CST",4
320 FIELD #1,4 AS FILE$
330 FOR A%=0 TO 2
340 FOR B%=0 TO 4
350 GET #1
360 CS(A%,B%)=CVS(FILE$)
370 NEXT B%:NEXT A%
380 CLOSE #1
390 LEV=1
420 GOSUB 2000
430 GOSUB 3000
440 GOSUB 4000
450 GOSUB 5000
460 GOSUB 6000
470 GOSUB 8000
475 IF COP%=8 THEN GOTO 490
480 GOSUB 8500
490 GOSUB 9500
495 IF COP%=8 OR COP%=7 THEN GOTO 525
500 GOSUB 7000
525 LEV=0:TGR=0:TOTSET=0:TOTFWS=0
530 LEV=LEV(BX%,J%)
540 IF DR%=0 THEN LEV=LEV-(MAN%)*YR(AX%/5,1):GOTO 560
550 LEV=LEV-(MAN%)*100/DR%
```

```
560 IF LT$<>"YES" THEN GOTO 580
570 LEV=LEV+VO(AX%/5,J%)/25*BR%*PR%
580 IF DR%=0 THEN LEV=LEV+SP%*YR(AX%/5,1):GOTO 595
590 LEV=LEV+SP%*100/DR%
595 IF GR$="N" THEN GOTO 640
600 IF DR%=0 THEN TGR=GR(J%):GOTO 607
603 IF COP%=8 THEN GOTO 640
604 IF COP%=9 OR COP%=6 THEN TGR=GR(J%):GOTO 607
605 TGR=GR(J%)*(((1+DR%/100)^YR(AX%/5,1))/((1+DR%/100)^YR(AX%/5,1)-1))
607 IF DR%=0 THEN TOTFWS=FWRATE*FAWS%*(1-
TAX%/100):TOTSET=SETA*5*(1-TAX%/100):GOTO 620
610 TOTFWS=(FWRATE*100/DR%)*(1-
(1/(1+DR%/100)^FAWS%))*(((1+DR%/100)^YR(AX%/5,1))/((1+DR%/100)^YR(AX%/5,
1)-1))*(1-TAX%/100)
611 TOTSET=(SETA*100/DR%)*(1-(1/(1+DR%/100)^5))*(((1+DR%/100)^YR
(AX%/5,1))/((1+DR%/100)^YR(AX%/5,1)-1))*(1-TAX%/100)
615 TGR=GR(J%)*(((1+DR%/100)^YR(AX%/5,1))/((1+DR%/100)^YR(AX%/5,1)-1))
620 LEV=LEV+TGR+TOTSET+TOTFWS+BLSUP
640 LEV=LEV-CS(AX%/5,J%)/25*TOT%
650 IF LEV-INT(LEV)<.5 THEN BPERP=INT(LEV) ELSE BPERP=INT(LEV)+1
730 CLS:LOCATE 4,5:PRINT"MANAGEMENT OPTION = ";OPT$:PRINT
735 IF YIELD$<>""THEN PRINT"(1) YIELD CLASS = ";YIELD$;" cu.m/ha/yr":GOTO
750
740 PRINT"(1) YIELD CLASS =";YR(AX%/5,0);"cu.m/ha/yr"
750 PRINT"    ROTATION LENGTH =";YR(AX%/5,1);"years"
780 IF BX%>=5 AND BX% <10 THEN PX%=BX%-5
790 IF BX%>=10 THEN PX%=BX%-10
795 IF BX%<5 THEN PX%=BX%
796 IF COP%<8 OR COP%>9 THEN GOTO 800
797 IF PX%=0 THEN PRINT"(2) LOW FUEL-WOOD PRICES.":GOTO 850
798 IF PX%=2 THEN PRINT"(2) MEDIUM FUEL-WOOD PRICES.":GOTO 850
799 IF PX%=4 THEN PRINT"(2) HIGH FUEL-WOOD PRICES.":GOTO 850
800 IF PX%=0 THEN PRINT"(2) LOW TIMBER / LOW FUEL-WOOD PRICES"
810 IF PX%=1 THEN PRINT"(2) LOW TIMBER / HIGH FUEL-WOOD PRICES"
820 IF PX%=2 THEN PRINT"(2) MEDIUM TIMBER / MEDIUM-FUEL WOOD PRICES"
830 IF PX%=3 THEN PRINT"(2) HIGH TIMBER / LOW FUEL-WOOD PRICES"
840 IF PX%=4 THEN PRINT"(2) HIGH TIMBER / HIGH FUEL-WOOD PRICES"
850 PRINT"(3) DISCOUNT RATE =";DR%;"%"
870 PRINT"(4) MANAGEMENT COSTS =";MAN%;"/ha/yr"
872 PRINT"(5) ADDITIONAL REVENUE FROM THE SALE OF LOP & TOP ? ";LT$;:IF
PR%=0 AND LT$="YES" THEN PRINT" (REVENUE NIL:see price)"ELSE PRINT
874 PRINT"(6) SPORTING RENTAL =";SP%;"/ha/yr"
875 IF LAND=1 THEN PRINT"(7) LAND TYPE:- PREVIOUSLY ARABLE (APPROVED
CROPS)"
876 IF LAND=2 THEN PRINT"(7) LAND TYPE:- PREVIOUSLY ARABLE (OTHER
CROPS)"
877 IF LAND=3 THEN PRINT"(7) LAND TYPE:- PREVIOUSLY, IMPROVED
GRASSLAND"
878 IF LAND=4 THEN PRINT"(7) LAND TYPE:- UNIMPROVED GRASSLAND IN
LFA's":GOTO 888
879 IF LAND=5 THEN PRINT"(7) LAND TYPE:- OTHER LAND"
880 IF DA$<>"" THEN PRINT "(7) AGRICULTURAL GRANT CATEGORY:- ";DA$
885 IF TGR=0 AND COP%=7 THEN PRINT"(7) GRANTS AT FIXED RATE DUE TO
COUP SIZE":GOTO 909
887 IF TGR=0 THEN PRINT"(7) NO GRANTS":GOTO 909
888 IF COP%=8 THEN PRINT"    NO GRANTS AVAILABLE FOR THIS
OPTION.":GOTO 909
889 IF GTYPE=4 THEN PRINT"(7) GRANTS:- FARM WOODLAND AND SET ASIDE
```

```
SCHEMES"
890 AS$=LEFT$(EXT$,1)
891 IF ASC(AS$)<49 OR ASC(AS$)>52 THEN PRINT"(7) NO GRANTS":GOTO 909
893 IF AS$="1" AND GTYPE=4 THEN PRINT"    FWS/Set-aside planting grants for
0.25-0.9ha":GOTO 906
894 IF AS$="2" AND GTYPE=4 THEN PRINT"    FWS/Set-aside planting grants for 1.0-
2.9ha":GOTO 906
895 IF AS$="3" AND GTYPE=4 THEN PRINT"    FWS/Set-aside planting grants for 3.0-
9.9ha":GOTO 906
896 IF AS$="4" AND GTYPE=4 THEN PRINT"    FWS/Set-aside planting grants for
over 10ha":GOTO 906
897 IF AS$="1" THEN PRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 0.25-
0.9ha,";
898 IF AS$="2" THEN PRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 1.0-
2.9ha,";
899 IF AS$="3" THEN PRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 3.0-
9.9ha,";
900 IF AS$="4" THEN PRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; OVER
10ha,";
901 IF GTYPE=1 THEN PRINT" ONLY"
902 IF GTYPE=2 THEN PRINT" AND BETTER LAND SUPPLEMENT"
903 IF GTYPE=3 THEN PRINT" AND FARM WOODLAND SCHEME"
904 IF GTYPE=5 THEN PRINT" AND SET ASIDE SCHEME"
906 IF GTYPE=2 THEN PRINT"    200 non-taxable payment at planting"
907 IF GTYPE=3 OR GTYPE=4 THEN PRINT"    Taxable payments made at a rate of
";FWRATE;:PRINT"for";FAWS%;:PRINT"years."
908 IF GTYPE=5 THEN PRINT"    Taxable payments made at a rate of ";SETA;" for five
years."
909 PRINT"(8) PERCENTAGE ALTERATION OF ESTABLISHMENT COSTS
=";TOT%;"%"
910 IF COP%>8 OR COP%<7 THEN PRINT"(9) LEVEL OF INCOME TAXATION
="TAX%;"%":PRINT ELSE PRINT
920 PRINT
925 PRINT"LEV FOR MANAGEMENT OPTION IN  PERPETUITY =";BPERP
927 PRINT:PRINT:PRINT"TYPE A NUMBER BETWEEN 1 & 9 TO TO ALTER THE
SITUATION DISPLAYED ABOVE.        TYPE 'P' FOR A PRINTOUT,  'Q' TO QUIT,
OR   'X' TO EXIT TO MAIN MENU."
929 IF X%=LX% AND LT$<>LASTLT$ THEN GOTO 937
931 IF LASTB=BPERP AND LASTD=LEV THEN LOCATE 18,53:PRINT"NO
ALTERATION" ELSE GOTO 937
932 IF X%=2 AND LX%=2 AND LT$=LASTLT$ THEN LOCATE 18,53:PRINT"NO
ALTERATION":GOTO 958
933 IF X%=5 AND LX%=5 AND LT$=LASTLT$ THEN LOCATE 18,53:PRINT"NO
ALTERATION":GOTO  958
935 GOTO 958
937 IF LASTB<>0 THEN LOCATE 19,53:PRINT"PREVIOUS LEV VALUE =";LASTB
940 IF X%=9 THEN LOCATE 18,53:PRINT"HAVE ALTERED TAXATION LEVEL"
941 IF X%=1 THEN LOCATE 18,53:PRINT"HAVE ALTERED YIELD CLASS"
942 IF X%=2 THEN LOCATE 18,53:PRINT"HAVE ALTERED PRICE REGIME"
943 IF X%=3 THEN LOCATE 18,53:PRINT"HAVE ALTERED DISCOUNT RATE"
944 IF X%=4 THEN LOCATE 18,53:PRINT"ALTERED MANAGEMENT COSTS"
945 IF X%=5 THEN LOCATE 18,53:PRINT"HAVE ALTERED LOP & TOP"
946 IF X%=6 THEN LOCATE 18,53:PRINT"HAVE ALTERED SPORTING RENTAL"
947 IF X%=7 THEN LOCATE 18,53:PRINT"HAVE ALTERED GRANT LEVEL"
948 IF X%=8 THEN LOCATE 18,53:PRINT"ALTERED ADDITIONAL COSTS"
958 LASTB=BPERP:LASTD=LEV:LASTLT$=LT$:LX%=X%
959 X%=6'ANY NUMBER WILL DO
960 WHILE X%<>0
```

```
970 ANS$=INKEY$:IF ANS$="" THEN GOTO 970
975 IF LEN(ANS$)>1 THEN GOTO 970
980 X%=ASC(ANS$)
990 IF (X%>48) AND (X%<58) THEN X%=0
1000 IF X%=88 OR X%=120 THEN X%=0
1005 IF X%=80 OR X%=112 THEN X%=0
1007 IF X%=81 OR X%=113 THEN X%=0
1010 WEND
1020 CLS:X%=ASC(ANS$)
1025 IF X%=80 OR X%=112 THEN GOSUB 31000:GOTO 525
1030 IF X%=81 OR X%=113 THEN GOTO 1999
1035 IF X%=88 OR X%=120 THEN GOTO 41000
1040 X%=X%-48:LX%=X%
1050 ON X% GOSUB 2000,3000,4000,5000,6000,8000,8500,9500,7000
1060 GOTO 525
1999 SYSTEM
2000 CLS:LOCATE 6,1:PRINT"PLEASE SELECT A PRODUCTIVITY LEVEL FOR
THIS OPTION.":PRINT
2010 FOR A%=0 TO 2
2015 YIELD$=""
2020 GOSUB 40000
2060 IF YIELD$<>"" AND A%=0 THEN PRINT TAB(20)"(1) LOW PRODUCTIVITY,
YIELD CLASS " YIELD$:PRINT
2070 IF YIELD$<>"" AND A%=1 THEN PRINT TAB(20)"(2) MEDIUM PRODUCTIVITY,
YIELD CLASS " YIELD$:PRINT
2080 IF YIELD$<>"" AND A%=2 THEN PRINT TAB(20)"(3) HIGH PRODUCTIVITY,
YIELD CLASS " YIELD$:PRINT
2090 NEXT A%
2100 IF YIELD$<>"" THEN GOTO 2240
2210 PRINT TAB(20) "(1) LOW    PRODUCTIVITY, YIELD CLASS"YR(0,0):PRINT
2220 PRINT TAB(20) "(2) MEDIUM PRODUCTIVITY, YIELD CLASS"YR(1,0):PRINT
2230 PRINT TAB(20) "(3) HIGH   PRODUCTIVITY, YIELD CLASS"YR(2,0):PRINT
2240 PRINT:PRINT"PRESS NUMBER FOR CHOICE (1-3)"
2245 LOCATE 2,45:PRINT OPT$
2250 GOSUB 20000
2260 IF ANS$="1" THEN AX%=0:A%=0:GOSUB 40000
2270 IF ANS$="2" THEN AX%=5:A%=1:GOSUB 40000
2280 IF ANS$="3" THEN AX%=10:A%=2:GOSUB 40000
2281 IF BX%>=5 AND BX%<10 THEN BX%=BX%-5
2282 IF BX%>=10 THEN BX%=BX%-10
2283 BX%=AX%+BX%
2290 RETURN
3000 IF COP%=9 OR COP%=8 THEN GOSUB 3500:RETURN
3005 LOCATE 6,1:PRINT"PLEASE SELECT THE PRICE REGIME FOR FUEL-WOOD
AND TIMBER MARKETS":PRINT"Prices should be chosen relative to the national
average prices            for fuel-wood and timber.":PRINT
3010 PRINT TAB(20) "(1) LOW TIMBER / LOW FUEL-WOOD PRICES":PRINT
3020 PRINT TAB(20) "(2) LOW TIMBER / HIGH FUEL-WOOD PRICES":PRINT
3030 PRINT TAB(20) "(3) MEDIUM TIMBER / MEDIUM FUEL-WOOD PRICES":PRINT
3040 PRINT TAB(20) "(4) HIGH TIMBER / LOW FUEL-WOOD PRICES":PRINT
3050 PRINT TAB(20) "(5) HIGH TIMBER / HIGH FUEL-WOOD PRICES":PRINT
3060 PRINT:PRINT"PRESS NUMBER FOR CHOICE (1-5)"
3065 LOCATE 2,45:PRINT OPT$
3070 GOSUB 10000
3080 IF ANS$="1" THEN BX%=AX%:PR%=0
3090 IF ANS$="2" THEN BX%=AX%+1:PR%=11
3100 IF ANS$="3" THEN BX%=AX%+2:PR%=6
3110 IF ANS$="4" THEN BX%=AX%+3:PR%=0
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3120 IF ANS$="5" THEN BX%=AX%+4:PR%=11
3130 RETURN
3500 LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"PLEASE SELECT THE PRICE
REGIME FOR FUEL WOOD MARKETS.":PRINT"Prices should be chosen relative to
the national average for fuel-wood.":PRINT
3510 PRINT TAB(20)"(1) LOW FUEL-WOOD PRICES":PRINT
3520 PRINT TAB(20)"(2) MEDIUM FUEL-WOOD PRICES":PRINT
3530 PRINT TAB(20)"(3) HIGH FUEL WOOD-PRICES":PRINT
3540 PRINT:PRINT"PRESS NUMBER OF CHOICE (1-3)."
3550 GOSUB 20000
3560 IF ANS$="1" THEN BX%=AX%:PR%=0
3570 IF ANS$="2" THEN BX%=AX%+2:PR%=6
3580 IF ANS$="3" THEN BX%=AX%+4:PR%=11
3590 RETURN
4000 CLS:LOCATE 6,1:PRINT "PLEASE SELECT A DISCOUNT RATE (To test rate of
return)":PRINT:PRINT TAB(20) "(1) DISCOUNT RATE = 0% (Net revenue)":PRINT
4010 PRINT TAB(20) "(2) DISCOUNT RATE = 2%":PRINT
4020 PRINT TAB(20) "(3) DISCOUNT RATE = 3%":PRINT
4030 PRINT TAB(20) "(4) DISCOUNT RATE = 4%":PRINT
4040 PRINT TAB(20) "(5) DISCOUNT RATE = 5%":PRINT
4050 PRINT"PRESS NUMBER OF CHOICE (1-5)"
4055 LOCATE 2,45:PRINT OPT$
4060 GOSUB 10000
4070 IF ANS$="1" THEN DR%=0
4080 IF ANS$="2" THEN DR%=2
4090 IF ANS$="3" THEN DR%=3
4100 IF ANS$="4" THEN DR%=4
4110 IF ANS$="5" THEN DR%=5
4115 IF DR%<>0 THEN J%=DR%-1 ELSE J%=DR%
4120 RETURN
5000 CLS:LOCATE 6,1
5010 PRINT "SELECT THE LEVEL OF MANAGEMENT COSTS EXPECTED":PRINT
5020 PRINT TAB(20) "(1) LOW       5/ha/yr":PRINT
5030 PRINT TAB(20) "(2) MEDIUM   8/ha/yr":PRINT
5040 PRINT TAB(20) "(3) HIGH      12/ha/yr":PRINT
5050 PRINT"PRESS NUMBER OF CHOICE (1-3)"
5055 LOCATE 2,45:PRINT OPT$
5060 GOSUB 20000
5070 IF ANS$="1" THEN MAN%=5
5080 IF ANS$="2" THEN MAN%=8
5090 IF ANS$="3" THEN MAN%=12
5110 RETURN
6000 LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"WILL YOU GENERATE EXTRA
REVENUE FROM THE SALE OF LOP AND TOP FOR FUEL-WOOD ?.":PRINT"This
will only be worthwhile if prices for fuel-wood are not low":PRINT
6010 GOSUB 30000
6020 IF ANS$="y" OR ANS$="Y" THEN LT$="YES" ELSE LT$="NO"
6030 RETURN
7000 CLS:IF COP%=8 OR COP%=7 THEN:LOCATE 6,1:PRINT"TAX RATE IS
IRRELEVANT IN THIS OPTION":PRINT:PRINT"PRESS ANY KEY TO
CONTINUE":ANS$=INPUT$(1):RETURN
7002 CLS:IF GTYPE <3 OR GR$="N" THEN LOCATE 6,1:PRINT"Tax rate is irrelevant
with the present grant choice, however, this information may be used if you alter the
type of grant"
7005 LOCATE 9,1:PRINT"Tax relief on expenditure in forestry is no longer legally
available, tax rate  is  only a consideration for those in receipt of annual payments from
the Farm  Woodland or Set Aside schemes."
7007 LOCATE 2,45:PRINT OPT$:LOCATE 13,1:PRINT"ENTER THE LEVEL  OF
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TAXATION  AT WHICH YOUR INCOME IS TAXED":PRINT"(The present upper and
lower limits are 40% and 25% respectively)"
7010 C%=0
7020 WHILE C%<=2
7030 ANS$=INKEY$:IF ANS$="" THEN GOTO 7030
7035 IF LEN(ANS$)>1 THEN GOTO 7030
7040 B%=ASC(ANS$)
7045 IF B%=88 OR B%=120 THEN GOTO 41000
7050 IF B%>47 AND B%<58 THEN C%=C%+1:PRINT CHR$(B%);:ELSE GOTO 7080
7060 IF C%=1 THEN TAX%=10*VAL(ANS$):GOTO 7080
7070 TAX%=TAX%+VAL(ANS$):C%=C%+1
7080 WEND
7085 PRINT:IF TAX%<5 OR TAX% >90 THEN PRINT"TRY AGAIN":GOTO 7010
7090 RETURN
8000 LOCATE 2,45:PRINT OPT$:LOCATE 6,1
8010 PRINT"WILL YOUR WOODLAND BE GENERATING ANY SPORTING RENTAL
?.":PRINT
8020 GOSUB 30000
8030 IF ANS$="N" OR ANS$="n" THEN CLS:SP%=0:RETURN
8040 LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"SELECT LEVEL OF SPORTING
RENTAL ":PRINT
8050 PRINT TAB(20) "(1) LOW    1/ha/yr":PRINT
8060 PRINT TAB(20) "(2) MEDIUM 8/ha/yr":PRINT
8070 PRINT TAB(20) "(3) HIGH   15/ha/yr":PRINT
8080 PRINT"PRESS NUMBER FOR CHOICE (1-3)"
8090 GOSUB 20000
8100 IF ANS$="1" THEN SP%=1
8110 IF ANS$="2" THEN SP%=8
8120 IF ANS$="3" THEN SP%=15
8130 RETURN
8500 IF COP%=8 THEN:LOCATE 6,1:PRINT"NO GRANTS AVAILABLE IN THIS
OPTION":PRINT"PRESS ANY KEY TO
CONTINUE.":GR$="N":ANS$=INPUT$(1):RETURN
8501 LAND=0:GTYPE=0:SETA=0:BLSUP=0:DA$=""
8502 IF COP%=7 THEN GOTO 9000
8505 CLS:LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"SELECT APPROPRIATE
TYPE OF GRANTS AND/OR ANNUAL PAYMENT":PRINT
8510 PRINT TAB(20)"(1) WOODLAND GRANT SCHEME ONLY":PRINT
8520 PRINT TAB(20)"(2) WOODLAND GRANT SCHEME AND BETTER LAND
SUPPLEMENT":PRINT
8530 PRINT TAB(20)"(3) WOODLAND GRANT SCHEME AND FARM WOODLAND
SCHEME":PRINT
8540 PRINT TAB(20)"(4) FARM WOODLAND SCHEME AND SET-ASIDE
SCHEME":PRINT
8550 PRINT TAB(20)"(5) WOODLAND GRANT SCHEME AND SET-ASIDE
SCHEME":PRINT
8560 PRINT TAB(20)"(6) NO GRANTS":PRINT:PRINT"PRESS NUMBER OF CHOICE
(1-6)"
8570 GOSUB 12000
8580 GTYPE=VAL(ANS$)
8585 IF ANS$="6" THEN GR$="N":DA$="":TGR=0:RETURN
8630 CLS:LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"SELECT APPROPRIATE
LAND TYPE (Grants vary with differing land types)":PRINT
8640 PRINT TAB(20)"(1) PREVIOUSLY ARABLE (APPROVED CROPS)":PRINT
8650 PRINT TAB(20)"(2) PREVIOUSLY ARABLE (OTHER CROPS)":PRINT
8660 PRINT TAB(20)"(3) PREVIOUSLY, IMPROVED GRASSLAND":PRINT
8670 PRINT TAB(20)"(4) UNIMPROVED GRASSLAND IN LESS FAVOURED
AREAS":PRINT
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8680 PRINT TAB(20)"(5) OTHER LAND":PRINT:PRINT"PRESS NUMBER FOR
CHOICE (1-5)"
8690 GOSUB 10000
8700 LAND=VAL(ANS$)
8750 IF LAND=5 AND GTYPE <>1 THEN PRINT:PRINT:PRINT"THIS COMBINATION
OF GRANT AND LAND IS NOT LEGALLY PERMISSABLE WITHIN THE
PROVISIONS OF THE GRANT SCHEME":GOSUB 13000:ANS$=INPUT$(1):GOTO
8505
8760 IF LAND=3 AND GTYPE >3 THEN PRINT:PRINT:PRINT"THIS COMBINATION
OF GRANT AND LAND IS NOT LEGALLY PERMISSABLE WITHIN THE
PROVISIONS OF THE GRANT SCHEME":GOSUB 13000:ANS$=INPUT$(1):GOTO
8505
8770 IF LAND=4 AND GTYPE =2 OR LAND =4 AND GTYPE >3 THEN
PRINT:PRINT:PRINT"THIS COMBINATION OF GRANTS AND LAND IS NOT
LEGALLY PERMISSABLE WITHIN THE      PROVISIONS OF THE GRANT
SCHEME":GOSUB 13000:ANS$=INPUT$(1):GOTO 8505
8780 IF LAND=2 AND GTYPE >3 THEN PRINT:PRINT:PRINT"THIS COMBINATION
OF GRANT AND LAND IS NOT LEGALLY PERMISSABLE WITHIN THE
PROVISIONS OF THE GRANT SCHEME":GOSUB 13000:ANS$=INPUT$(1):GOTO
8505
8790 IF GTYPE=1 THEN FWRATE=0:BLSUP=0:SETA=0:GOTO 9000
8800 IF GTYPE=1 THEN FWRATE=0:BLSUP=0:SETA=0:GOTO 9000
8810 IF GTYPE=2 THEN FWRATE=0:BLSUP=200:SETA=0:GOTO 9000
8820 IF LAND=4 AND GTYPE =3 THEN FWRATE=30:BLSUP=0:SETA=0:GOTO 9000
8830 CLS:LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"SELECT APPROPRIATE
AGRICULTURAL LAND CLASSIFICATION":PRINT
8840 PRINT TAB(20)"(1) NOT WITHIN A LESS FAVOURED AREA":PRINT
8850 PRINT TAB(20)"(2) LESS FAVOURED AREA (DISADVANTAGED AREA)":PRINT
8860 PRINT TAB(20)"(3) LESS FAVOURED AREA (SEVERELY DISADVANTAGED
AREA)":PRINT
8870 PRINT:PRINT"PRESS NUMBER OF CHOICE (1-3)"
8880 GOSUB 20000
8881 IF ANS$="1" THEN DA$="NOT A LESS FAVOURED AREA"
8882 IF ANS$="2" THEN DA$="LESS FAVOURED AREA (disadvantaged)"
8883 IF ANS$="3" THEN DA$="LESS FAVOURED AREA (severely disadvantaged)"
8890 IF ANS$="1" AND GTYPE >2 AND GTYPE <5 THEN
FWRATE=190:BLSUP=0:SETA=0:GOTO 9000
8900 IF ANS$="2" AND GTYPE >2 AND GTYPE <5 THEN
FWRATE=150:BLSUP=0:SETA=0:GOTO 9000
8910 IF ANS$="3" AND GTYPE >2 AND GTYPE <5 THEN
FWRATE=100:BLSUP=0:SETA=0:GOTO 9000
8920 IF ANS$="1" AND GTYPE=5 THEN FWRATE=0:BLSUP=0:SETA=200:GOTO
9000
8930 IF ANS$="2" AND GTYPE=5 THEN FWRATE=0:BLSUP=0:SETA=180:GOTO
9000
8940 IF ANS$="3" AND GTYPE=5 THEN FWRATE=0:BLSUP=0:SETA=180
9000 LOCATE 6,1:PRINT"SELECT APPROPRIATE GRANT LEVEL (Grant varies with
size of area planted).":PRINT
9020 PRINT TAB(20)"(1) 0.25-0.9ha.":PRINT
9030 PRINT TAB(20)"(2) 1.0-2.9ha.":PRINT
9040 PRINT TAB(20)"(3) 3.0-9.9ha.":PRINT
9050 PRINT TAB(20)"(4) 10ha OR MORE":PRINT:PRINT"PRESS NUMBER FOR
CHOICE (1-4)"
9055 LOCATE 2,45:PRINT OPT$
9060 GOSUB 11000
9065 EXT$=RIGHT$(EXT$,4)
9072 IF ANS$="1" AND FWRATE <>0 THEN CLS:PRINT:PRINT:PRINT"THE
MINIMUM BLOCK SIZE FOR PLANTING GRANTS UNDER THE FARM WOODLAND
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SCHEME      IS 1 - 2.9 ha":PRINT:PRINT"(PRESS ANY KEY, AND RE-
SELECT)":ANS$=INPUT$(1):GOTO 9000
9075 GR$="Y"
9080 EXT$=CHR$(ASC(ANS$))+EXT$
9100 IF FWRATE <>0 AND COP%=2 THEN OPEN "R",#1,"A:\ETSU\FWCP"+EXT$,4
ELSE OPEN "R",#1,GRANT$+EXT$,4
9120 FIELD #1,4 AS FILE$
9130 FOR B%=0 TO 4
9140 GET #1
9150 GR(B%)=CVS(FILE$)
9160 NEXT B%
9170 CLOSE #1
9190 RETURN
9500 CLS:LOCATE 2,45:PRINT OPT$:LOCATE 6,1
9510 PRINT"WILL YOUR PARTICULAR SITUATION REQUIRE ADJUSTMENT TO
ESTABLISHMENT COSTS?.":PRINT"(Refer to documentation, or OFI occasional paper
No 35, for a full account     of costs already considered).":PRINT
9520 GOSUB 30000
9530 IF ANS$="N" OR ANS$="n" THEN CLS:TOT%=0:RETURN
9531 LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"DO YOU WISH TO EXAMINE
THE CASH FLOW BEFORE  MAKING COST ADJUSTMENTS ?.":PRINT
9532 GOSUB 30000
9533 IF ANS$="N" OR ANS$="n" THEN CLS:GOTO 9540
9534 PRINT OPT$:PRINT TAB(15)"CASH FLOW FOR MEDIUM YIELD, PRICES AND
3% DISCOUNT RATE":PRINT"OPERATION";TAB(20)"YEAR";TAB(28)"VOLUME
cu.m";TAB(40)"PRICE ";TAB(50)"VALUE ";TAB(60)"CUM VAL ";TAB(70)"DISC VAL
":FOR A=0 TO 19
9535 IF KEV(A,0)=0 AND KEV (A,1)=0 THEN A=19:GOTO 9538
9536 IF KEV(A,1)=1 THEN PRINT KEV$(A);TAB(20)KEV(A,0);TAB(30)"
-";TAB(40)KEV(A,2);TAB(50)CINT(KEV(A,1)*KEV(A,2));:CUML%=CUML%+
INT(KEV(A,1)*KEV(A,2)):PRINT TAB(60)CUML%;TAB(71)INT(1/(1.03)^KEV(A,0)
*KEV(A,1)*KEV(A,2)):GOTO 9538
9537 PRINT
KEV$(A);TAB(20)KEV(A,0);TAB(30)KEV(A,1);TAB(40)KEV(A,2);TAB(50)INT(KEV(A,1)
*KEV(A,2));:CUML=CUML+INT(KEV(A,1)*KEV(A,2)):PRINT TAB(60)CUML;TAB(71)
INT(1/(1.03)^KEV(A,0)*KEV(A,1)*KEV(A,2))
9538 NEXT A:CUML=0:LOCATE 24,65:PRINT"PRESS ANY KEY";
9539 ANS$=INKEY$:IF ANS$="" THEN GOTO 9539
9540 IF LEN(ANS$) >1 THEN GOTO 9539
9541 IF ANS$="X" OR ANS$="x" THEN GOTO 41000
9542 CLS:LOCATE 2,45:PRINT OPT$:LOCATE 6,1:PRINT"ENTER PERCENTAGE
VALUE FOR ESTABLISHMENT COSTS":PRINT"Any two figure number between -99
and 99, the computer expects two figures so  use -01, -02, 06, 07 etc. Negative values
indicate reduced costs.":PRINT
9543 PRINT"PERCENTAGE"TAB(21)"10%"TAB(27)"20%"TAB(33)"30%"TAB(39)"40%"
TAB(45)"50%"TAB(51)"60%"TAB(57)"70%"TAB(63)"80%"TAB(69)"90%":COSTS%=
CS(AX%/5,J%)*(((1+DR%/100)^YR(AX%/5,1))-1)/(1+DR%/100)^YR(AX%/5,1):IF
DR%=0 THEN COSTS%=CS(AX%/5,J%)
9544 IF OPT$="Oak coppice (normalised age)." THEN PRINT"EQUIVALENT POUNDS
";TAB(20)" 5";TAB(26)" 10";TAB(32)" 15";TAB(38)" 20";TAB(44)" 26";TAB(50)"
31";TAB(56)" 36";TAB(62)" 41";TAB(68)" 46":GOTO 9548
9546 PRINT"EQUIVALENT POUNDS
";TAB(20)INT(COSTS%/25*10);TAB(26)INT(COSTS%/25*20);TAB(32)INT(COSTS%
/25*30);TAB(38)INT(COSTS%/25*40);TAB(44)INT(COSTS%/25*50);TAB(50)INT(COSTS%
/25*60);TAB(56)INT(COSTS%/25*70);TAB(62)INT(COSTS%/25*80);
9547 PRINT TAB(68)INT(COSTS%/25*90)
9548 PRINT:PRINT"DISCOUNT RATE =";DR%;"%";:PRINT"  YIELD CLASS =";:IF
YIELD$="" THEN PRINT YR(AX%/5,0):PRINT ELSE PRINT YIELD$:PRINT
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9549 C%=0:NUM$=""
9550 WHILE C%<2
9560 ANS$=INKEY$:IF ANS$="" THEN GOTO 9560
9565 IF LEN(ANS$)>1 THEN GOTO 9560
9570 B%=ASC(ANS$)
9571 IF B%=88 OR B%=120 THEN GOTO 41000
9575 IF B%=45 THEN PRINT ANS$;:NUM$=CHR$(45):GOTO 9600
9580 IF B%>47 AND B%<58 THEN PRINT ANS$;:C%=C%+1:ELSE GOTO 9600
9590 NUM$=NUM$+ANS$
9600 WEND
9610 TOT%=VAL(NUM$)
9620 RETURN
10000 A%=6'ANY NUMBER WILL DO
10010 WHILE A%<>0
10020 ANS$=INKEY$:IF ANS$="" THEN GOTO 10020
10025 IF LEN(ANS$)>1 THEN GOTO 10020
10030 A%=ASC(ANS$)
10035 IF A%=88 OR A%=120 THEN GOTO 41000
10040 IF (A%>48) AND (A%<54) THEN A%=0
10050 WEND
10060 CLS
10070 RETURN
11000 A%=6'ANY NUMBER WILL DO
11010 WHILE A%<>0
11020 ANS$=INKEY$:IF ANS$="" THEN GOTO 11020
11025 IF LEN(ANS$)>1 THEN GOTO 11020
11030 A%=ASC(ANS$)
11035 IF A%=88 OR A%=120 THEN GOTO 41000
11040 IF (A%>48) AND (A%<53) THEN A%=0
11050 WEND
11060 CLS
11070 RETURN
12000 A%=6'ANY NUMBER WILL DO
12010 WHILE A%<>0
12020 ANS$=INKEY$:IF ANS$="" THEN GOTO 12020
12025 IF LEN(ANS$)>1 THEN GOTO 12020
12030 A%=ASC(ANS$)
12035 IF A%=88 OR A%=120 THEN GOTO 41000
12040 IF (A%>48) AND (A%<55) THEN A%=0
12050 WEND
12060 CLS
12070 RETURN
13000 PRINT:PRINT"ELIGIBILITY TABLE OF GRANT SCHEMES vs LAND
TYPES":PRINT:PRINT"LAND TYPE";TAB(35)"GRANTS":PRINT
13010 PRINT TAB(26)"WGS Only";TAB(37)"WGS & BLS";TAB(49)"FWS
Only";TAB(59)"FWS & SA";TAB(70)"WGS & SA":PRINT
13020 PRINT"Arable (approved
crops)";TAB(26)"Yes";TAB(37)"Yes";TAB(49)"Yes";TAB(59)"Yes";TAB(70)"Yes"
13030 PRINT"Arable (other
crops)";TAB(26)"Yes";TAB(37)"Yes";TAB(49)"Yes";TAB(59)"No";TAB(70)"No"
13040 PRINT"Improved
grassland";TAB(26)"Yes";TAB(37)"Yes";TAB(49)"Yes";TAB(59)"No";TAB(70)"No"
13050 PRINT"Unimproved
grassland,LFA";TAB(26)"Yes";TAB(37)"No";TAB(49)"Yes";TAB(59)"No";TAB(70)"No"
13060 PRINT"Other agricultural
land";TAB(26)"Yes";TAB(37)"No";TAB(49)"No";TAB(59)"No";TAB(70)"No"
13070 PRINT:PRINT"KEY":PRINT"WGS = Woodland Grant Scheme":PRINT"BLS =
Better Land Supplement":PRINT"FWS = Farm Woodland Scheme":PRINT"SA  = Set
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Aside Scheme":PRINT"LFA = Less Favoured Area"
13080 PRINT:PRINT"PRESS ANY KEY"
13090 RETURN
20000 A%=6'ANY NUMBER WILL DO
20010 WHILE A%<>0
20020 ANS$=INKEY$:IF ANS$="" THEN GOTO 20020
20025 IF LEN(ANS$)>1 THEN GOTO 20020
20030 A%=ASC(ANS$)
20035 IF A%=88 OR A%=120 THEN GOTO 41000
20040 IF (A%>48) AND (A%<52) THEN A%=0
20050 WEND
20060 CLS
20070 RETURN
30000 PRINT TAB(20)"(Y)  YES":PRINT
30010 PRINT TAB(20)"(N)  NO":PRINT
30015 LOCATE 2,45:PRINT OPT$
30020 A%=6:WHILE A%<>0
30030 ANS$=INKEY$:IF ANS$="" THEN GOTO 30030
30035 IF LEN(ANS$)>1 THEN GOTO 30030
30040 A%=ASC(ANS$)
30045 IF A%=88 OR A%=120 THEN GOTO 41000
30050 IF A%=89 OR A%=121 THEN A%=0
30060 IF A%=78 OR A%=110 THEN A%=0
30070 WEND
30080 CLS
30090 RETURN
31000 LPRINT"    MANAGEMENT OPTION = ";OPT$:LPRINT
31010 IF YIELD$<>""THEN LPRINT"(1) YIELD CLASS = ";YIELD$;" cu.m/ha/yr":GOTO
31030
31020 LPRINT"(1) YIELD CLASS =";YR(AX%/5,0);"cu.m/ha/yr"
31030 LPRINT"    ROTATION LENGTH =";YR(AX%/5,1);"years"
31040 IF COP%<8 OR COP%>9 THEN GOTO 31080
31050 IF PX%=0 THEN LPRINT"(2) LOW FUEL-WOOD PRICES.":GOTO 31130
31060 IF PX%=2 THEN LPRINT"(2) MEDIUM FUEL-WOOD PRICES.":GOTO 31130
31070 IF PX%=4 THEN LPRINT"(2) HIGH FUEL-WOOD PRICES.":GOTO 31130
31080 IF PX%=0 THEN LPRINT"(2) LOW TIMBER / LOW FUEL-WOOD PRICES"
31090 IF PX%=1 THEN LPRINT"(2) LOW TIMBER / HIGH FUEL-WOOD PRICES"
31100 IF PX%=2 THEN LPRINT"(2) MEDIUM TIMBER / MEDIUM-FUEL WOOD
PRICES"
31110 IF PX%=3 THEN LPRINT"(2) HIGH TIMBER / LOW FUEL-WOOD PRICES"
31120 IF PX%=4 THEN LPRINT"(2) HIGH TIMBER / HIGH FUEL-WOOD PRICES"
31130 LPRINT"(3) DISCOUNT RATE =";DR%;"%"
31140 LPRINT"(4) MANAGEMENT COSTS =";MAN%;"/ha/yr"
31150 LPRINT"(5) ADDITIONAL REVENUE FROM THE SALE OF LOP & TOP ?
";LT$;:IF PR%=0 AND LT$="YES" THEN LPRINT" (REVENUE NIL:see price)"ELSE
LPRINT
31160 LPRINT"(6) SPORTING RENTAL =";SP%;"Pounds/ha/yr"
31170 IF LAND=1 THEN LPRINT"(7) LAND TYPE:- PREVIOUSLY ARABLE
(APPROVED CROPS)"
31180 IF LAND=2 THEN LPRINT"(7) LAND TYPE:- PREVIOUSLY ARABLE (OTHER
CROPS)"
31190 IF LAND=3 THEN LPRINT"(7) LAND TYPE:- PREVIOUSLY, IMPROVED
GRASSLAND"
31200 IF LAND=4 THEN LPRINT"(7) LAND TYPE:- UNIMPROVED GRASSLAND IN
LFA's":GOTO 31240
31210 IF LAND=5 THEN LPRINT"(7) LAND TYPE:- OTHER LAND"
31220 IF DA$<>"" THEN LPRINT "(7) AGRICULTURAL GRANT CATEGORY:- ";DA$
31230 IF TGR=0 THEN LPRINT"(7) NO GRANTS":GOTO 31430
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31240 IF COP%=8 THEN LPRINT"    NO GRANTS AVAILABLE FOR THIS
OPTION.":GOTO 31430
31250 IF GTYPE=4 THEN LPRINT"(7) GRANTS:- FARM WOODLAND AND SET
ASIDE SCHEMES"
31260 AS$=LEFT$(EXT$,1)
31270 IF ASC(AS$)<49 OR ASC(AS$)>52 THEN LPRINT"(7) NO GRANTS":GOTO
31430
31280 IF AS$="1" AND GTYPE=4 THEN LPRINT"    FWS/Set-aside planting grants for
0.25-0.9ha":GOTO 31400
31290 IF AS$="2" AND GTYPE=4 THEN LPRINT"    FWS/Set-aside planting grants for
1.0-2.9ha":GOTO 31400
31300 IF AS$="3" AND GTYPE=4 THEN LPRINT"    FWS/Set-aside planting grants for
3.0-9.9ha":GOTO 31400
31310 IF AS$="4" AND GTYPE=4 THEN LPRINT"    FWS/Set-aside planting grants for
over 10ha":GOTO 31400
31320 IF AS$="1" THEN LPRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 0.25-
0.9ha,";
31330 IF AS$="2" THEN LPRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 1.0-
2.9ha,";
31340 IF AS$="3" THEN LPRINT"(7) GRANTS:- WOODLAND GRANT SCHEME; 3.0-
9.9ha,";
31350 IF AS$="4" THEN LPRINT"(7) GRANTS:- WOODLAND GRANT SCHEME;
OVER 10ha,";
31360 IF GTYPE=1 THEN LPRINT" ONLY"
31370 IF GTYPE=2 THEN LPRINT" AND BETTER LAND SUPPLEMENT"
31380 IF GTYPE=3 THEN LPRINT" AND FARM WOODLAND SCHEME"
31390 IF GTYPE=5 THEN LPRINT" AND SET ASIDE SCHEME"
31400 IF GTYPE=2 THEN LPRINT"    200 non-taxable payment at planting"
31410 IF GTYPE=3 OR GTYPE=4 THEN LPRINT"    Taxable payments made at a rate
of ";FWRATE;"for";FAWS%;"years."
31420 IF GTYPE=5 THEN LPRINT"    Taxable payments made at a rate of ";SETA;" for
five years."
31430 LPRINT"(8) PERCENTAGE ALTERATION OF ESTABLISHMENT COSTS
=";TOT%;"%"
31440 IF COP%>8 OR COP%<7 THEN LPRINT"(9) LEVEL OF INCOME TAXATION
="TAX%;"%":LPRINT ELSE LPRINT
31470 LPRINT"LEV FOR MANAGEMENT OPTION IN  PERPETUITY
=";BPERP:LPRINT:LPRINT
31480 RETURN
40000 IF OPT$="Oak / Ash / Cherry." THEN
YIELD$=STR$(YR(A%,0)):YIELD$=MID$(YIELD$,2,1)+" / "+MID$(YIELD$,3,1)+" /
"+RIGHT$(YIELD$,1)
40005 IF OPT$="30 year Oak / Ash / Cherry." THEN
YIELD$=STR$(YR(A%,0)):YIELD$=MID$(YIELD$,2,1)+" / "+MID$(YIELD$,3,1)+" /
"+RIGHT$(YIELD$,1)
40010 IF OPT$="Beech / Corsican Pine." THEN
YIELD$=STR$(YR(A%,0)):YIELD$=MID$(YIELD$,2,1)+" / "+RIGHT$(YIELD$,2)
40020 IF OPT$="Douglas Fir / Oak." THEN
YIELD$=STR$(YR(A%,0)):YIELD$=MID$(YIELD$,2,2)+" / "+RIGHT$(YIELD$,1)
40030 IF OPT$="Oak / Ash group system from coppice." THEN
YIELD$=STR$(YR(A%,0)):YIELD$=MID$(YIELD$,2,1)+" / "+RIGHT$(YIELD$,1)
40040 RETURN
41000 CLOSE:CHAIN"A:\ETSU\MEN2",67
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